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SAND DRIFT AT PORTLAND, VICTORIA

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Abstract

Conclusions concerning the movement of sands over long-term periods, as determined from detailed studies of the mineral compositions, grain sizes and solubilities of existing beach and harbour floor sands in the Portland district accord with results obtained from the short-term tracing of the movement of marker minerals added at significant points to the sea floor and the beaches.

The evidence from these studies indicates that coastwise littoral drift into the Harbour region from east or west is of minor significance. Most effects in the Harbour are caused by seasonal variations of onshore and offshore drift. Existing conditions of equilibrium in the Harbour region are likely to be upset by construction of the Main Breakwater and the Lee Breakwater, necessitating regular dredging operations.

Introduction

A study of the grain sizes and compositions of the beach and Harbour floor sands in relation to the geology of the Portland district, south-western Victoria (Mineragraphic Report No. 622), followed by the tracing of the movements of marker minerals added to the sea floor and to certain of the beaches, at significant points (Mineragraphic Report No. 635), was undertaken in the Mineragraphic Investigations Laboratory, C.S.I.R.O., at the request of the Portland Harbour Trust Commission.

The purpose of the study was to explore the movement of sand along the coast in relation to the new harbour at present under construction on the sheltered eastern side of Bridgewater Promontory, facing eastwards into Portland Bay.

Along the 90 miles of coastline included in this study, it was necessary to examine the sand groups from three principal units, namely:

(a) Discovery Bay in the west of the area, extending for 32 miles from Descartes Bay, past the mouth of the Glenelg River to the South Australian border;

(b) Bridgewater Promontory, extending for some 21 miles from Cape Bridgewater to Point Danger; and

(c) Portland Bay, including the Harbour region, trending NNW for six miles from Point Danger to beyond Whaler's Point, thence NE for eight miles to Narrawong, and then easterly and south-easterly for 22 miles to the south-eastern side of the mouth of the Eumeralla River.

The Discovery Bay coastline is formed of almost continuous beach sands, broken only by small outcrops of dune limestone at Noble's Rocks and Sutton's Rocks. The backshore region consists of a series of E-W trending sub-parallel sand dunes, largely devoid of vegetation and rising to heights of 100 ft. or more (Coulson, 1940).

The Bridgewater Promontory coastline consists of bold cliffs 200 to 450 ft. high where three composite volcanoes of olivine basalt flows and tuff beds (Coulson, 1941) are situated at Cape Bridgewater, Cape Nelson and Cape Grant. These are connected by stretches of sandy beaches forming Bridgewater Bay and Nelson Bay, backed for most of their length by continuous sand dunes, except at the sheltered western end of Bridgewater Bay.

The Portland Bay coastline is comprised of a short western shoreline consisting of cliffs of basalt and tuff in parts, alternating with occasional pocket beaches as far as Double Corner, beyond Whaler's Point. In the Portland Harbour region, cliffs of Tertiary limestone are capped by basalt in the vicinity of Whaler's Point. Beyond Double Corner the coastline swings in a broad arc past Narrawong, Tyrendarra and Yambuk to Cape Reamur, and the coast consists of sandy beaches backed by a low coastal plain and vegetated dune ridges in the west, the sand dunes becoming bare of cover and rising higher east of Tyrendarra.

The Surrey, Fitzroy and Eumeralla Rivers, emptying into Portland Bay, drain an area composed essentially of Tertiary olivine basalts and tuffs. The Glenelg River, emptying into Discovery Bay, traverses a terrain of Pre-Cambrian granites, schists and gneisses, Permian glacials, Mesozoic sediments and Tertiary limestones, sands and clays.

Wind Directions

A wind analysis for Portland, covering the period 1941-1945, kindly supplied by the Commonwealth Meteorological Bureau, reveals that the sum total of onshore winds is 64% to 75% of all winds with speeds greater than 13 m.p.h., and 58% of all winds with speeds between 8 and 12 m.p.h.

Of these, the south-westerly winds blow throughout the year, but more especially in the months of February-March and October-November. They are also the strongest winds, comprising 50% of all winds with speeds greater than 31 m.p.h., 34% of all winds with speeds between 19 and 31 m.p.h., and 30% of all winds with speeds between 13 and 18 m.p.h. The south-westerlies are thus the dominant winds in respect to sand drift. The only sections of the coast shielded from them, by west of north trending cliffs of basalt, are limited to the western ends of Portland Bay (i.e., the Harbour region) and Bridgewater Bay respectively. Such sections of the coast are devoid of sand dunes. On the other hand, sand dunes are developed in the backshore regions of all other sections of the three principal coastal units, except in exposed areas where bold cliffs of basalt are lapped by the sea. The variation in height of the dunes corresponds more or less to the degree of exposure to the south-westerlies.

South-easterlies blow chiefly from December to April and comprise 19%, 10% and 12½% respectively of all winds of velocities from 13 to 18, 19 to 31 and over 31 m.p.h. Their effect on coastwise sand drift is thus not expected to be of any marked significance compared with the south-westerlies, while southerly and easterly winds are even less frequent and less powerful.

Westerly winds blow chiefly from August to January and, along with the north-westerly winds, must affect the disposition of sand dunes along Discovery Bay. The north-westerlies, however, are not likely to promote sand drift along the beaches, inasmuch as they have little or no fetch in this region.

Offshore winds blowing from the north and north-east have their greatest frequency from May to September. They constitute 61% of all winds with speeds between 1 and 7 m.p.h., and are unlikely to promote sand drift along the coast.

Field Sampling

Sampling of the beach and harbour floor sands was conducted by the Portland Harbour Trust engineers in two stages (I) during May and June, 1954, in order to obtain representative samples for detailed study, prior to the selection of suitable marker minerals, and (II) during June to October, 1955, to obtain test samples for the detection of the marker minerals.

Samples collected during stage I were obtained at the stations shown in Figs. 1 and 2. The sand samples studied are grouped as follows:

(i) Discovery Bay—a series of 46 samples (Nos. 1-46) was taken. Sampling stations were spaced at two-mile intervals. At each station three samples were taken, one at low water mark, one at high water mark, and one at the foot of the dunes, where present.

(ii) Portland Bay—a series of 22 samples (Nos. 101-122) was taken at intervals along Portland Bay beaches at low water mark, eastwards from the Dutton Way.

(iii) Bridgewater Promontory—a series of 9 samples (Nos. 200-208) was taken at intervals along Bridgewater Bay and Nelson Bay at low water mark.

(iv) Portland Harbour Beaches—a series of 8 samples (Nos. 123-130) was taken at irregular intervals from the pocket beaches and the main harbour beach at Portland at low water mark. Two of these samples, Nos. 129 and 130 are anomalous. They were taken above and below high water mark, about 100 ft. apart, adjacent to the Portland Harbour Trust Offices, where material excavated from the Boat Harbour area had been dumped previously.

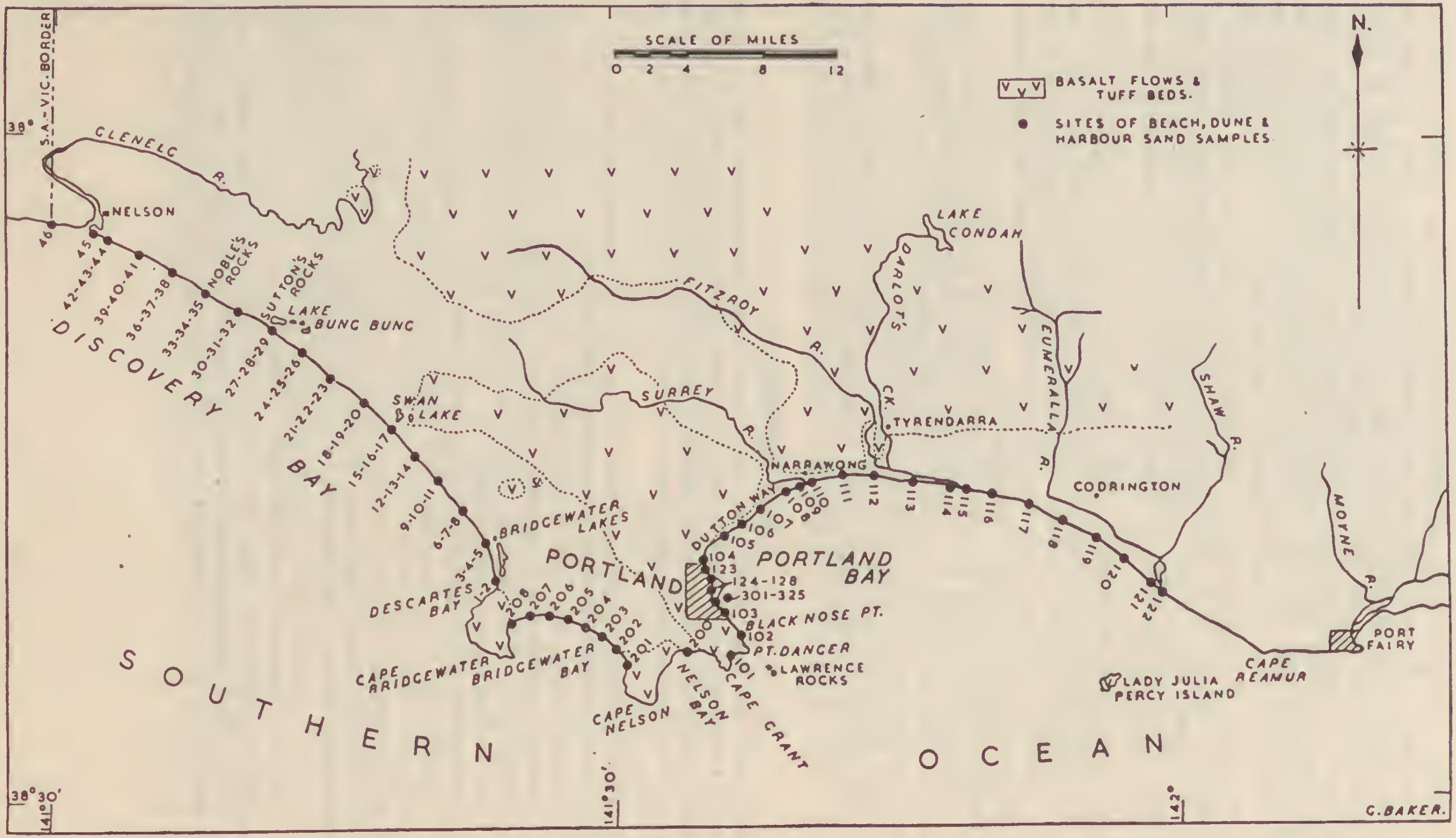

Fig. 1.—Sketch map of the Portland district showing sites of sampled beach and dune sands. Sampled May, 1954. (Based on Portland Harbour Trust Plan XII4, Sheet 1, 1954. Distribution of Basaltic Rocks from Coulson, 1941.)

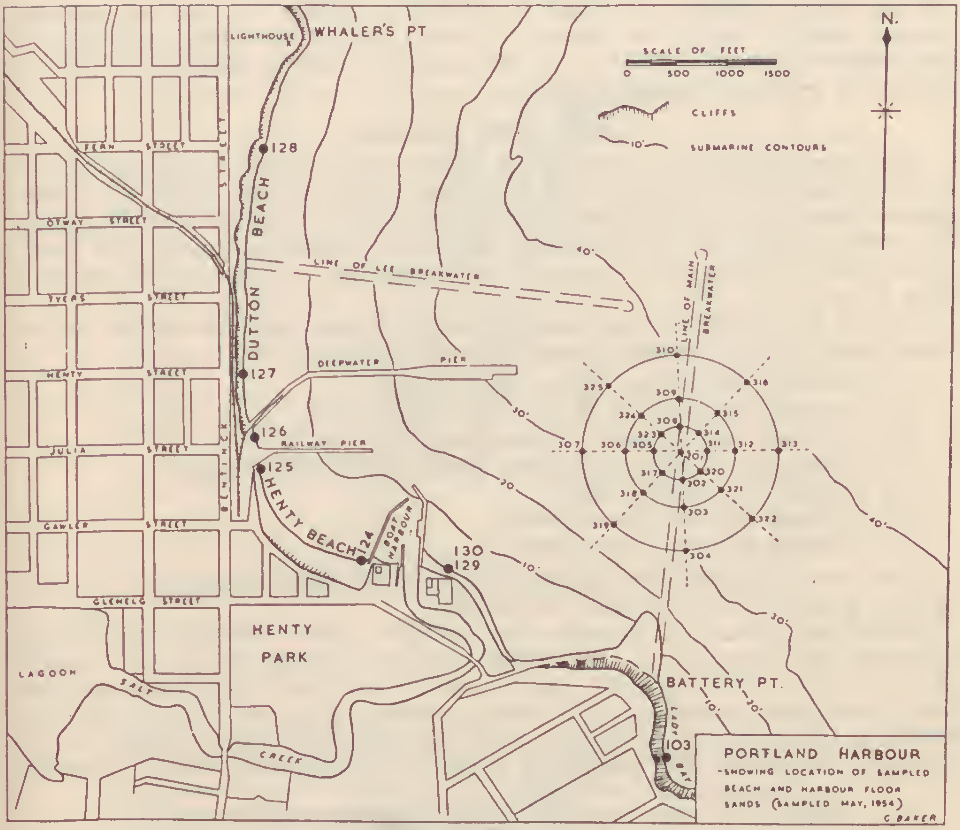

Fig. 2.—Sketch map of the Portland Harbour area showing location of sampled beach and harbour floor sands. Sampled May, 1954. (Based on Portland Harbour Trust Plan X114, Sheets 2 and 2A, 1954.)

(v) Portland Harbour Floor—a series of 24 samples (Nos. 301-325) was taken from the harbour floor at stations located as shown in Fig. 2.

In sampling the beach sands, a sample of about 2 c.ft. was cut with a spade. The sample was then quartered down to about 1000 grams, dried and sized through B.S.S. sieves. The sea floor samples were taken with a small grab, at a depth of 30 to 40 ft. below sea level. The depth of bite was 6 to 12 in., and the sample approximated to 1 c.ft. Each was quartered down to 1000 grams, dried and sized. All of the grab samples brought up sand except at station No. 307, which yielded friable sandstone encrusted with recent marine organisms.

Most of the beach sands were sampled from within the swash zone, where the effects of sand re-sorting by the wind are minimized.

Test samples, collected in the same way during stage II, were taken at various intervals of time at several groups of stations (see under "Movement of Marker Minerals"). All but the —52 mesh fractions were rejected, since the marker minerals were of —52 mesh size. Five hundred gram samples were examined, and positive results notified to Portland Harbour Trust officers so that new sampling stations could be taken up as required. Samples were always taken, if possible, at two adjacent stations, so that the rate of progress of marker mineral drift could be checked by positive and negative results.

Mechanical Analyses

Each sand sample was sized through B.S.S. sieves and the weighed quantities from each have been expressed on a percentage basis in Tables 2 to 8 of Mineragraphic Report No. 622. All but one sample yielded size fractions within the range 7-14 mesh, 14-25 mesh, 25-52 mesh, 52-100 mesh, 100-200 mesh and —200 mesh. From these percentages were prepared the cumulative frequency curves shown in Figs. 3 to 9.

Figs. 3 to 9 facilitate comparisons of grain size distribution among the various sands themselves, and between groups of sands arranged thus:

(1) Discovery Bay—Low Water Mark Sands.
(2) Discovery Bay—High Water Mark Sands.
(3) Discovery Bay—Foot of Dunes Sands.
(4) Bridgewater Promontory Beach Sands.
(5) Portland Bay Beach Sands.
(6) Portland Harbour Beach Sands.
(7) Portland Harbour Floor Sands.

The curves reveal that the majority of the sampled sands have a relatively small range of grain size and are mostly well sorted.

From these curves (*cf.* Krumbein and Pettijohn, 1938; Pettijohn, 1949) three significant values, namely (a) the median parameter (Md), (b) the first quartile (Q_1), and (c) the third quartile (Q_3), as well as two quartile measures calculated from these values, namely (i) the sorting coefficient (So) and (ii) the skewness coefficient (Sk), have been determined for each sand sample (see Tables 9 to 15, Mineragraphic Report No. 622). The ranges of the significant values and of the

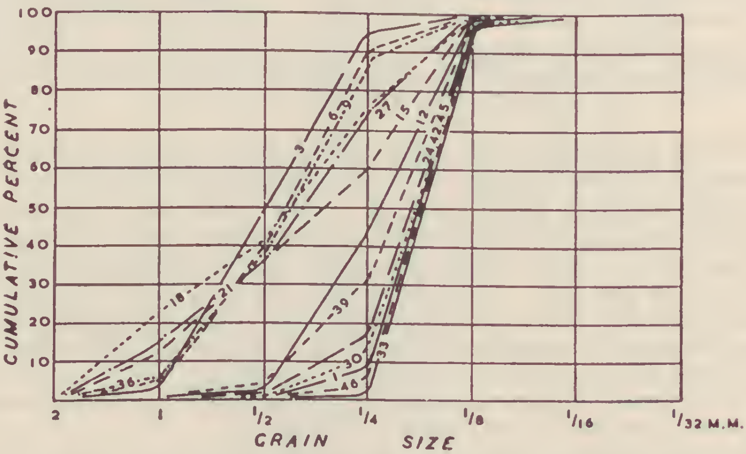

Fig. 3.—Cumulative frequency curves showing grain size distribution of Discovery Bay low water mark sands (samples 1-46).

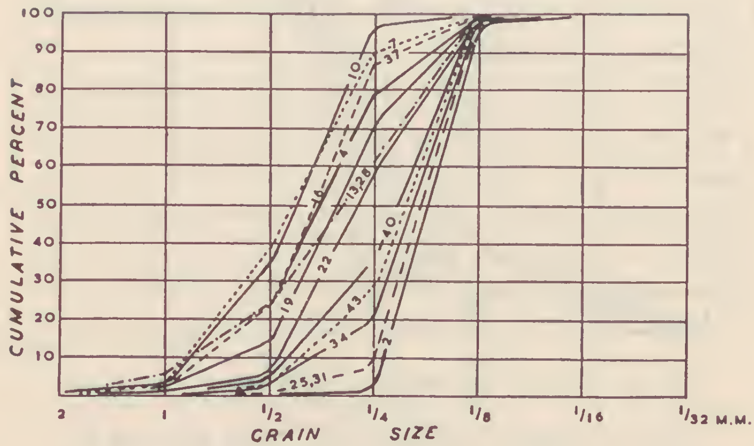

FIG. 4.—Cumulative frequency curves showing grain size distribution of Discovery Bay high water mark sands (samples 2-43).

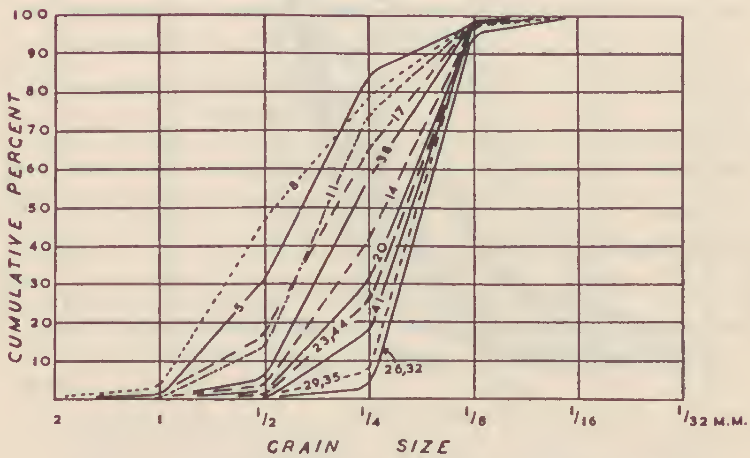

FIG. 5.—Cumulative frequency curves showing grain size distribution of Discovery Bay foot of dunes sands (samples 5-44).

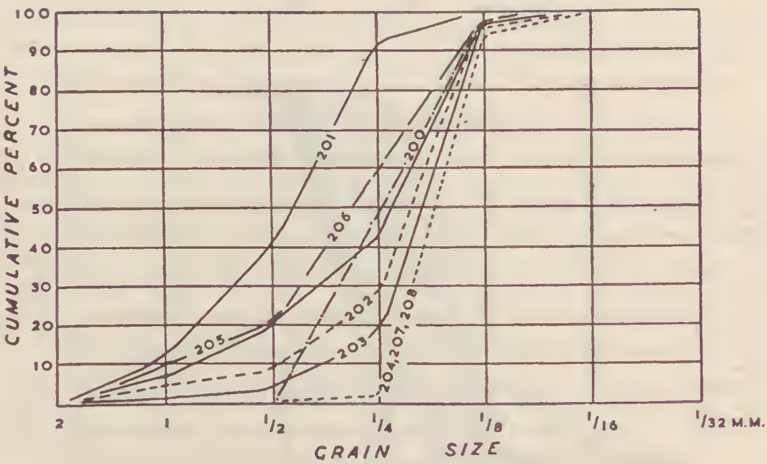

FIG. 6.—Cumulative frequency curves showing grain size distribution of Bridgewater Promontory beach sands (samples 200-208).

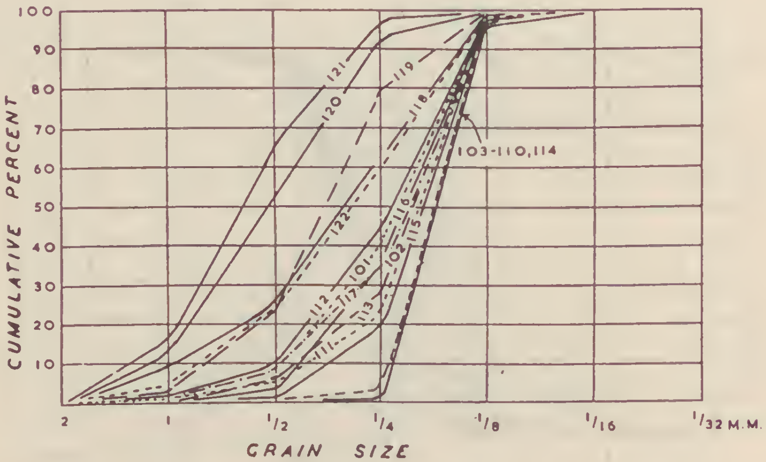

FIG. 7.—Cumulative frequency curves showing grain size distribution of Portland Bay beach sands (samples 101-122).

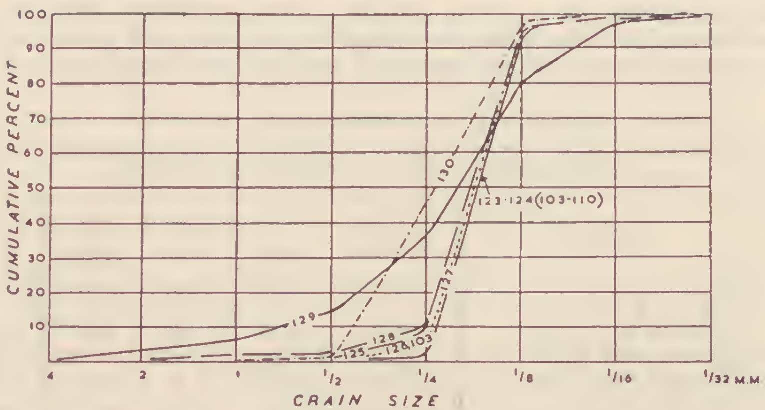

Fig. 8.—Cumulative frequency curves showing grain size distribution of Portland Harbour beach sands (samples 103, 104 and 123-130).

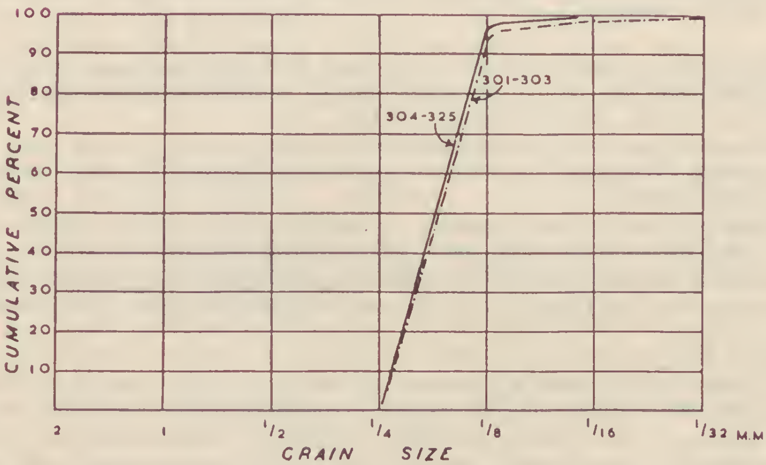

Fig. 9.—Cumulative frequency curves showing grain size distribution of Portland Harbour floor sands (samples 301-325).

quartile measures for each group of sands have been compared in Table 16, Mineragraphic Report No. 622. Their average values are presented herein in Table 1, which compares the summarized results of the mechanical analyses, and confirms

TABLE 1

Averages of Significant Values and of Quartile Measures of Portland District Marine Beach Sands, Dune Sands and Harbour Floor Sands

Group No.	Location	Sample Numbers	Md (m.m.)	Q_3 (m.m.)	Q_1 (m.m.)	So	Sk
1	Discovery Bay, Low Water Mark Sands	1–46	0·29	0·46	0·20	1·45	1·07
2	Discovery Bay, High Water Mark Sands	2–43	0·29	0·40	0·21	1·36	1·02
3	Discovery Bay, Foot of Dunes Sands	5–44	0·25	0·34	0·14	1·32	1·00
4	Bridgewater Promontory Beach Sands	200–208	0·23	0·34	0·15	1·36	1·08
5	Portland Bay Beach Sands	101–122	0·25	0·34	0·18	1·33	1·03
6	Portland Harbour Beach Sands (Natural)	123–128	0·18	0·22	0·15	1·21	1·02
7	Portland Harbour Beach Sands (Dumped Material)	129–130	0·23	0·36	0·16	1·53	1·10
8	Portland Harbour Floor Sands	301–325	0·18	0·21	0·15	1·18	0·98

Key: Md = Median; Q_3, Q_1 = Quartiles; So = Sorting coefficient; Sk = Skewness ("Symmetry") coefficient.

the field observation that the Portland Harbour floor and beach sands are distinctly finer-grained than the sands of the other beaches, with the exception of the sand at the sheltered western end of Bridgewater Bay.

The average values in Table 1 also show that the backshore sands from the foot of dunes along Discovery Bay are somewhat finer-grained than the sands at low and high water marks.

The majority of the sands provide unimodal, narrow, steeply peaked size frequency distributions. Only rare examples (Nos. 18 and 202—see Fig. 1) reveal a slight tendency towards bimodal distributions, and in them the primary mode is in the medium to fine sand range, with a lesser mode in the coarser sand sizes.

Sorting

The more closely a sand approaches uniformity in grain size (i.e., falls within a single size fraction), the closer its sorting coefficient (So) approaches unity.

It is apparent from Table 1 and Figs. 3-9 that the harbour floor sands are the most uniform of those tested, and that where not contaminated with dumped material the harbour beach sands are only slightly less uniform in grain size. Approximately 95% to 98% of the sand in any one sample falls within a single size fraction. The sands from the other beaches are markedly less well sorted, with a significant spread over three or four size fractions, the Discovery Bay sands showing the greater distribution over more than one fraction.

Along Discovery Bay, the backshore sands are better sorted than the low water mark sands. Coupled with their rather finer grain size, this is attributed to the superposition of wind sorting upon previous wave sorting for the backshore sands.

The more closely the distribution of grain size becomes symmetrical about the median parameter, the more nearly the skewness coefficient (Sk) approaches unity. A bias towards the coarser sizes results in a figure greater than unity, while a bias towards the finer sizes yields a figure less than unity. Table 1 shows that where the harbour floor and harbour beach sands are not contaminated with dump material there is almost symmetrical distribution of grain size, but with a slight negative skewness. The wind-worked backshore sands of Discovery Bay have very symmetrical grain size distribution. The other beach sands show a slight positive skewness, being somewhat asymmetrically skewed towards the coarser sizes.

Lateral Variations

Grain size and degree of sorting vary laterally along the several beaches, as shown graphically in Fig. 10.

Along Discovery Bay (Fig. 10, D and E) the grain size is at a maximum and the degree of sorting at a minimum over the central section between Swan Lake and Sutton's Rocks. The grain size falls sharply to a minimum in the lee of Sutton's Rocks and of Noble's Rocks, and the degree of sorting increases sympathetically. The same trend holds for the backshore sands (Fig. 10, C), with the fine-grained, well-sorted section extending from south-east of Sutton's Rocks to north-west of Noble's Rocks. By breaking up the waves, these two rocky projections evidently reduce wave energy, thus permitting the accumulation of finer-grained sand in their vicinities.

Along Bridgewater Bay (Fig. 10, A) there is a rather irregular increase in grain size of the sand from west to east, the finer-grained sands having accumulated at the sheltered western end, with a second section of relatively fine-grained and well-sorted sand in the lee of rocky outcrops at Shelly Beach.

Along Portland Bay (Fig. 10, F) the grain size increases and the degree of sorting decreases more or less progressively from west to east, corresponding to increasing degrees of exposure to wave attack from the south-west.

Solubility Analyses

The proportions of soluble and insoluble constituents in the various size fractions of the sands were determined as a preliminary to studying their mineral content. The results are listed in Tables 18 to 24 of Mineragraphic Report No. 622. They generally confirm Coulson's (1940, p. 319) observation that the Portland Harbour beach sands are more than 90% acid soluble (1 : 1 HCl), while Discovery Bay sands are approximately 75% acid soluble.

The acid soluble portions consist essentially of well-polished fragments of shells, etc. (= organogenic fragments). Insoluble residues consist mainly of quartz, with fragments of basalt in places and minor amounts of 42 other minerals. Locally there are significant accumulations of artificial substances such as slag, bottle glass, etc.

The percentages of insoluble material in each size fraction of the sands from the various sand groups (Fig. 11) and the ratios of soluble to insoluble material determined therefrom (see Tables 25 to 31, Mineragraphic Report No. 622) reveal several interesting trends. The range and average values of the solubility ratios are shown in Table 2.

Discovery Bay

At Descartes Bay, situated at the south-eastern end of Discovery Bay beach, insoluble material constitutes about 40% of the sand, and is partly basaltic material

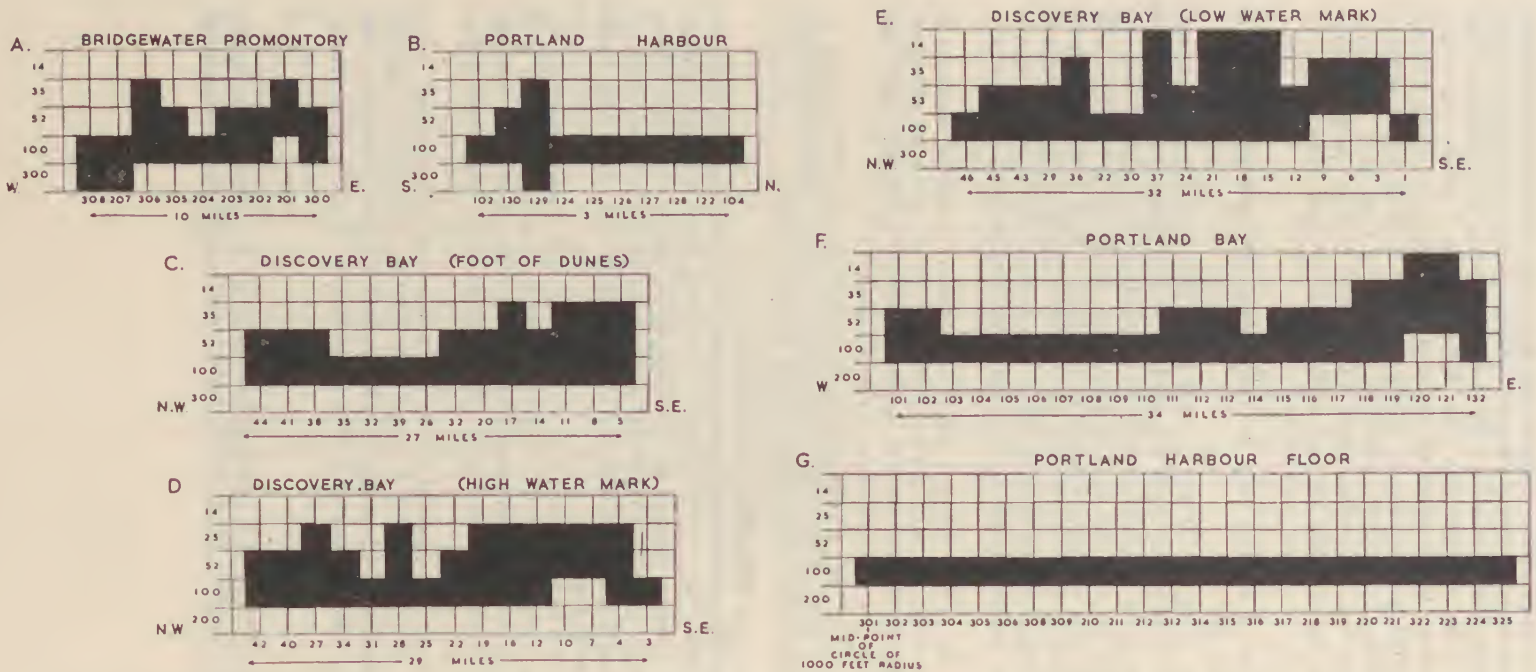

Fig. 10.—Diagram showing distribution of the predominant grade sizes in each sample of the several sand groups from the Portland district.

A—Bridgewater Promontory beach sands. From Cape Bridgewater to Nelson Bay (samples 200-208).
B—Portland Harbour beach sands. From Lady Bay to north of Whaler's Point (samples 103, 104 and 123-130).
C—Discovery Bay foot of dunes sands. From near the eastern bank, mouth of the Glenelg River to Bridgewater Lakes (samples 5-44).
D—Discovery Bay high water mark sands. From one mile south-east of the mouth of the Glenelg River to Descartes Bay (samples 2-43).
E—Discovery Bay low water mark sands. From the South Australian-Victorian border to Descartes Bay (samples 1-46).
F—Portland Bay beach sands. From Cape Grant to the mouth of the Eumeralla River (samples 101-122).
G—Portland Harbour floor sands. From a circular area of 2000 ft. diameter with centre located on the line of projected Main Breakwater, and situated 4600 ft. east of the corner of Julia St. and Bentinck St. in Portland (samples 301-325).

(Figures at left-hand end of each diagram represent B.S.S. grade sizes; figures beneath each diagram refer to sample numbers shown on Fig. 1.)

TABLE 2

Ranges and Average Values of Solubility Ratios of Portland Sands

Group Number	Location	Sample Numbers	Range in Solubility Ratio	Average Solubility Ratio
1	Discovery Bay Low Water Mark Sands	1–46	1·5–12·7	4·5
2	Discovery Bay High Water Mark Sands	2–43	1·5–12·4	3·3
3	Discovery Bay Foot of Dunes Sands	5–44	1·9–15·4	3·8
4	Bridgewater Promontory Beach Sands	200–208	1·9–22·8	7·3
5	Portland Bay Beach Sands	101–122	1·1–70·4	17·7 (15·0 including Nos. 123–128)
6	Portland Harbour Beach Sands (Natural)	123–128	1·9–6·8	5·1 (7·7 including Nos. 103 & 104)
7	Portland Harbour Beach Sands (Dumped Material)	129–130	0·5–0·7	0·6
8	Portland Harbour Floor Sands	301–325	9·8–20·3	13·2

derived from the Cape Bridgewater basalts, partly quartz. In a north-westerly direction along the beach the amount of basaltic material decreases, but the insoluble matter is maintained at 35% to 40% (see Fig. 11, D) for about six miles, partly as a result of the concentration of artificial slag along this section of the beach. Further north-west the insoluble content falls to 25% to 30% and consists essentially of quartz grains. This content of insoluble material is maintained for about sixteen miles as far as a position approximately two miles north-west of Noble's Rocks, after which it declines to about 7% on approaching the mouth of the Glenelg River.

The insoluble material in the Discovery Bay sands is uniformly distributed through the sizing fractions from +25 to +200 mesh, with some tendency to decline in the —200 mesh fraction.

Bridgewater Bay

In Bridgewater Bay the insoluble content of the sands falls from about 35% at the eastern end of the bay to about 25% in the central section of the beach, and then to about 5% at the extreme western end (Fig. 11, A). Over the central section, quartz is the chief insoluble component, but at the western end this is augmented by basaltic material. The trend parallels that shown in Discovery Bay. The percentage of insoluble material is more or less uniform in each size fraction.

Portland Bay

The Portland Bay sands show a generally similar trend, but in the reverse direction (Fig. 11, C); local accumulations of slag and small variations in the vicinity of river mouths affect the trend to some extent. At the south-western end of the Bay, along the section from Cape Grant to Blacknose Point, there is a

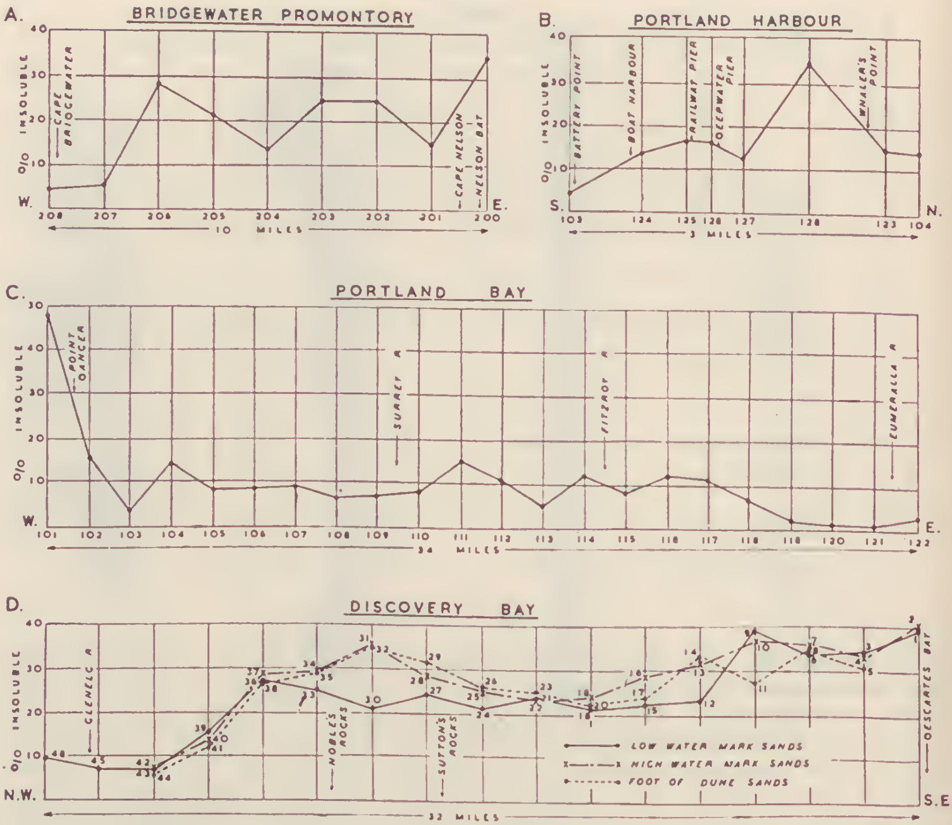

FIG. 11.—Graphs showing variation of the insoluble residue percentages of the Portland district beach and dune sands.

A—Bridgewater Promontory beach sands (samples 200-208).
B—Portland Harbour beach sands (samples 103, 104 and 123-128).
C—Portland Bay beach sands (samples 101-122).
D—Discovery Bay foot of dunes sands (samples 5-44), high water mark sands (samples 2-43), and low water mark sands (samples 1-46).

concentration of basaltic material which raises the insoluble content to nearly 50% of the total sand. From Lady Bay, where the basalt recedes from the cliffs, north-eastward and then eastward to a point four miles east of the mouth of the Fitzroy River, quartz is the predominant insoluble component, and the insoluble content of the sands averages 10%, rising to 15% where slag is locally abundant. East from this point, in the vicinity of the Eumeralla River mouth, the insoluble content declines to less than 2% of the sand.

Whereas the trend is similar to that shown by the Discovery Bay sands, there is a significantly lower content of insoluble material along the section where quartz is the principal insoluble component. The insoluble material is about equally high in the +100 and +200 mesh fractions, but declines in the +52 mesh and coarser fractions, as well as in the —200 mesh fraction.

In the harbour beaches, the insoluble content is about 15% of the sand, except in sample 128, which contains an unusually high proportion of basaltic material, and in sand derived from the dumped material near the Harbour Trust offices, where the sand has not yet achieved a state of equilibrium with the natural beach sands. The sample from below high water mark (No. 130) has progressed further towards equilibrium than the sample from above high water mark (No. 129).

On the harbour floor there is less basaltic material, and the insoluble content, which is largely quartz, is correspondingly lower than for the harbour beaches, averaging 6% to 8% (Fig. 12). In the harbour beach sands, and even more noticeably in the harbour floor sands, there is a sharp increase in the insoluble content of the finer size fractions, particularly in the —200 mesh fraction, compared with the coarser size fractions. The insoluble content in the —200 mesh fraction is 20% to 25%, which approximates the content of quartz in the central sections of Discovery Bay and Bridgewater Bay.

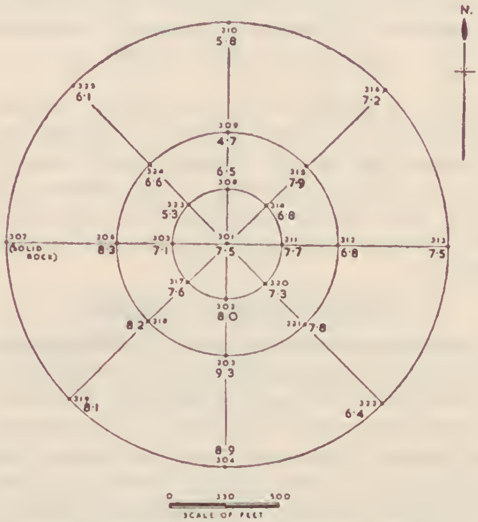

FIG. 12.—Diagram showing variation of the insoluble residue percentages of the Portland Harbour floor sands (samples 301-325). (Smaller figures represent locations of samples; larger figures represent percentages of insoluble residues.)

Grain Size of Insoluble Material

The percentages of insoluble material in the +52 fractions of the various sands (see Tables 33 to 39, Mineragraphic Report No. 622) emphasize the distinctive finer grain size of the harbour sands, where less than 5% of the +52 mesh fractions consist of insoluble minerals, as compared with 50% to 90% in the Discovery Bay and Bridgewater Bay sands. The Portland Bay sands show a clear transition both to east and west of the harbour area into coarser sands with a high insoluble content in the +52 mesh fractions. Only in the small amounts of the —200 fractions of the harbour sands does the concentration of insoluble matter approximate to the concentrations found in the sands occurring on the exposed beaches.

It is evident that if sand is drifting into the harbour area it is leaving most of its insoluble mineral matter behind.

Colour of the Soluble Shelly Matter

The sands of Discovery Bay, the exposed eastern section of Bridgewater Bay and the exposed eastern section of Portland Bay are white sands, whereas the 95% acid soluble sands of Portland Harbour and the sheltered western portion of Portland Bay, also the equally acid soluble sands from the sheltered western end of Bridgewater Bay, are grey in colour, as noted by Coulson (1940, p. 320), and they have a pepper-and-salt appearance. This appearance arises principally from the presence of a high proportion of dark coloured shell fragments, which are largely lacking or of only minor significance in the white sands on the more exposed beaches.

The colour difference is attributed to a change in the fauna supplying shelly detritus. The distribution of the fauna appears to be related to sea bottom conditions, organisms developing darker coloured shells being concentrated in the relatively sheltered waters and on adjacent rocky sections of the coast.

The significance of such colour variations is in proving that a great deal of the sand in Portland Harbour has originated on the harbour floor, and has not drifted in from a distance.

Heavy Mineral Analyses

Since the second stage of the investigations of sand movement along the Portland coast concerned the addition of distinctive marker minerals to the beach and harbour floor sands, and the recognition of these in minute proportions, it was necessary to study in detail the minerals present even as traces in the various sands. Apart from ubiquitous quartz and a little felspar in places, the sands contain 42 other mineral species, most of which occur in very minor amounts and belong to the group of heavy minerals with densities in excess of that of heavy liquid (bromoform having a specific gravity of 2·86). In view of their sparsity in the sands, these heavy minerals are treated herein as natural tracer minerals.

Tests on the various sizing fractions of typical sands revealed that the grain size of these heavy minerals is such that they are concentrated in the —52 fractions, and only negligible amounts occur in the +52 fractions, with the exception of one or two sands sampled close to basaltic cliffs. It was found, however, that the acid treatment of the +52 mesh fractions released a small proportion of —52 mesh sand originally cemented to shell fragments, and this included some heavy mineral grains. Accordingly, the acid insoluble residues of the +52 mesh fractions of each sand subsequently treated were bulked and sieved on a 52 mesh screen. The grains passing through were added to the —52 fractions, and the heavy minerals extracted from the composite —52 mesh product, ignoring coarser fractions.

The weight of heavy mineral concentrate obtained from bromoform treatment was calculated as a percentage of the total —52 mesh fraction. This percentage constitutes the heavy mineral index number recorded for each of the sampled sands (Figs. 13 and 14). The range and average values of the index numbers are shown in Table 3.

Magnetic Minerals

Magnetic minerals, consisting mainly of magnetite, were detected in the heavy mineral concentrates with an Alnico hand magnet, prior to mounting for examination under the microscope.

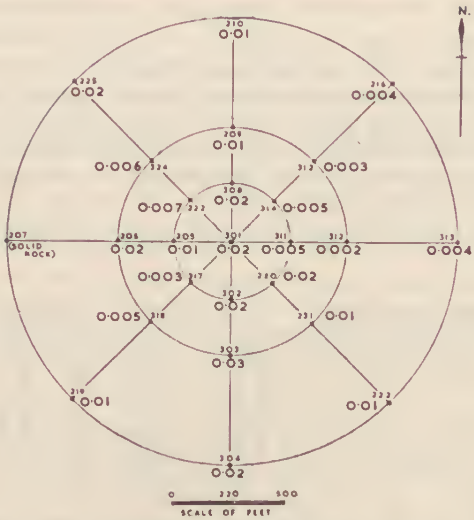

FIG. 13.—Diagram showing variation of the heavy mineral (—52 B.S.S.) index numbers of the Portland Harbour floor sands (samples 301-325). (Smaller figures represent locations of samples; larger figures represent index numbers.)

They occur as rare to occasional grains in the high water mark and foot of dune sands from Discovery Bay, and are somewhat more frequent in low water mark sands. They tend to increase in amount west of the Glenelg River (sample No. 46) and in Descartes Bay close to the basalts of Cape Bridgewater (sample Nos. 1, 3, 5 and 6).

TABLE 3

Ranges and Average Values of Index Numbers of —52 (B.S.S.) Fractions of the Several Groups of the Portland Sands

Group Number	Location	Sample Numbers	Range of Index Numbers	Average Index Numbers
1	Discovery Bay Low Water Mark Sands	1–46	0·003–0·50	0·07
2	Discovery Bay High Water Mark Sands	2–43	0·02–0·45	0·13
3	Discovery Bay Foot of Dunes Sands	5–44	0·01–0·23	0·05
4	Bridgewater Promontory Beach Sands	200–208	0·006–2·43	0·44
5	Portland Bay Beach Sands	101–122	0·003–0·32	0·05
6	Portland Harbour Beach Sands (Natural)	123–128	0·07–0·67 (0·009–0·67 including Sample Nos. 103 & 104)	0·24 (0·15 including Sample Nos. 103 & 104)
7	Portland Harbour Beach Sands (Dumped Material)	129–130	5·9–16·5	11·20
8	Portland Harbour Floor Sands	301–325	0·002–0·03	0·01

The sands from the Bridgewater Promontory beaches contain only a few magnetic grains.

In Portland Bay, they show notable concentrations on the western sides of the mouths of the Fitzroy and Eumeralla Rivers, and at sampling station No. 128 on Portland Harbour beach they amount to a "flood". A polished briquette of the heavy mineral concentrate from No. 128 reveals that the chief magnetic mineral present is maghemite (gamma-Fe_2O_3), which can be matched in the cliff section nearby, and is thus of purely local origin.

The harbour floor sands contain very few magnetic grains.

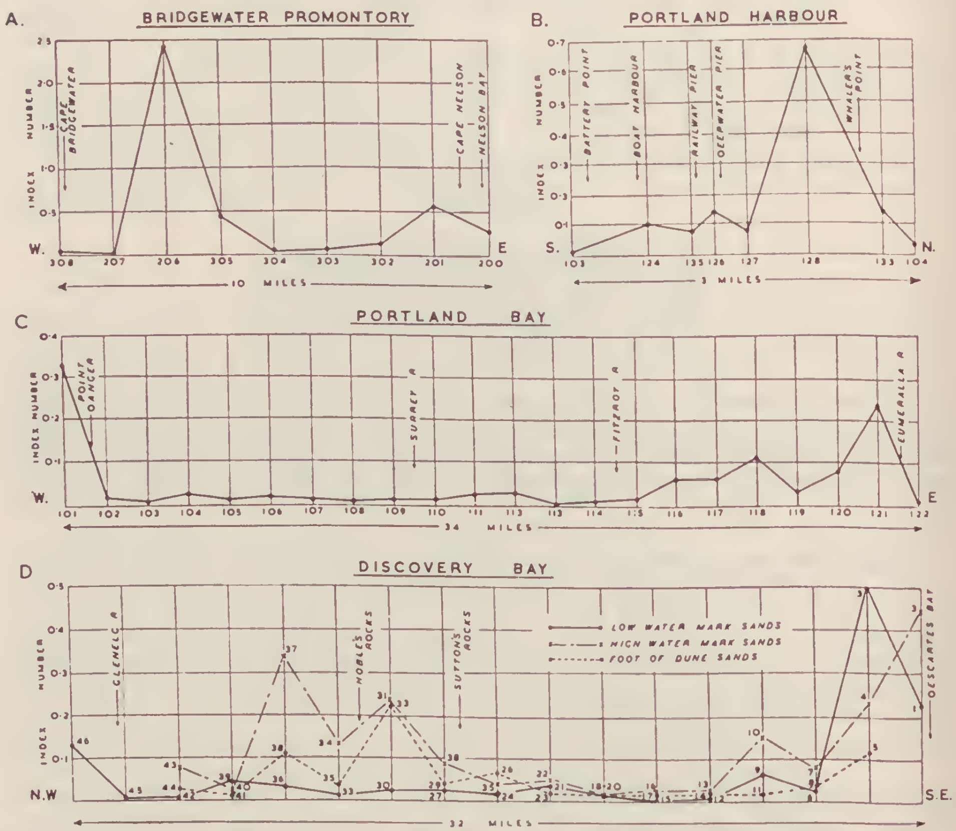

FIG. 14.—Graphs showing variation of the heavy mineral (—52 B.S.S.) index numbers of the Portland district beach and dune sands.

A—Bridgewater Promontory beach sands (samples 200-208).
B—Portland Harbour beach sands (samples 103, 104 and 123-128).
C—Portland Bay beach sands (samples 101-122).
D—Discovery Bay foot of dunes sands (samples 5-44), high water mark sands (samples 2-43), and low water mark sands (samples 1-46).

Heavy Mineral Assemblages

The minerals present in the heavy concentrates were mounted in Canada balsam and identified under the petrological microscope. Then, using a minimum of 15 fields of view, a grain count was made of the various mineral species present for each of the 109 sampled sands. Not less than 1000 grains were recorded for each sample, except where the total heavy mineral assemblage contained less than this number, when all the grains present were recorded. In assemblages containing a high concentration of opaque minerals the grain counts were increased to 1500 to 1800 grains so that minor amounts of transparent heavy minerals should not be overlooked.

The proportions of the various minerals present, expressed as percentages of the heavy mineral concentrate, together with the number of grains counted for each sample, are listed in Tables 41 to 48 of Mineragraphic Report No. 622. The average percentages for the several groups of samples are listed herein in Table 4.

TABLE 4

Average Percentage by Count Values of —52 (B.S.S.) Mineral Species in the Heavy Mineral Assemblages of the Portland Sands

Mineral Species	I %	II %	III %	IV %	V %	VI %	VII %
Anatase	0·1	0·1	0·1	0·02	0·03	0	0·05
Andalusite	0·8	0·7	0·6	Pr.	0·1	Pr.	0·08
Augite	1·5	1·1	0·7	5·2	24·9	36·8	55·4
Brookite	Pr.	Pr.	Pr.	0	Pr.	0	0
Cassiterite	0·2	0·06	0·08	0	0·05	Pr.	0·05
Cyanite	0·5	0·2	0·3	0	0·009	0·05	0·01
Dolomite	0	0·006	0·2	0·04	0·6	0·05	0
Epidote	2·4	1·1	1·2	0·2	0·4	Pr.	0·4
Garnet	1·8	1·7	1·7	0·5	0·4	0·03	0·19
Hornblende	2·9	1·1	1·3	0·4	0·6	0·1	1·0
Hypersthene	0·07	0·05	0·007	Pr.	0·01	0	0·03
Iddingsite	0·3	0·03	Pr.	0·02	0·5	1·1	—
Leucoxene	4·8	3·3	3·0	1·2	1·9	1·3	0·7
Monazite	0·7	0·8	0·8	0·2	0·09	Pr.	0·03
Olivine	2·7	1·4	0·3	53·1	3·8	4·5	2·5
Opaque Minerals	52·0	56·1	58·3	28·4	58·0	54·7	36·8
Rutile	3·3	3·0	3·6	1·1	0·8	0·07	0·3
Sillimanite	Pr.	0·08	0·07	0·06	0·005	0	0·1
Spinel	0·1	0·2	0·06	0·03	0·02	0	0·03
Staurolite	1·0	0·8	0·5	0·1	0·1	0·05	0·04
Topaz	0·3	0·9	0·5	Pr.	0·05	0	0·07
Tourmaline	4·3	5·3	3·6	0·5	0·7	0·1	0·4
White Mica	0·1	0·05	0	0·07	0·2	0·1	0·3
Zircon	18·6	21·5	22·7	8·3	6·7	1·0	1·3
Zoisite	1·4	0·3	0·3	0	0·1	0·05	0·1
INDEX NUMBER	0·07	0·13	0·05	0·44	0·05	0·24	0·01

(Pr. = present in minute amounts)

I—Discovery Bay low water mark sands.
II—Discovery Bay high water mark sands.
III—Discovery Bay foot of dunes sands.
IV—Bridgewater Promontory beach sands.
V—Portland Bay beach sands.
VI—Portland Harbour beach sands.
VII—Portland Harbour floor sands.

The heavy minerals found in the sands fall broadly into two distinct groups of very different origin, namely:

(1) Basaltic minerals—olivine, augite and iddingsite, which are notably angular and are derived from local sources—the basalts and tuffs exposed in the cliffs of Bridgewater Promontory; and

(2) Granitic and metamorphic etc. minerals — anatase, andalusite, brookite, cassiterite, cyanite, epidote, garnet, hornblende, monazite, rutile, sillimanite, spinel, staurolite, topaz, tourmaline white mica, zircon and zoisite, which are mostly well-rounded and are derived from distant sources—granitic, metamorphic and sedimentary rocks not exposed in the cliffs or in the immediate environment, though outcropping upstream in the valley of the Glenelg River and tributaries.

Some other minerals, like the opaque minerals, though abundant, could be derived from either of these sources, while the dolomite present is authigenic.

This grouping makes it possible to trace the spread of minerals shed from the basalts and tuffs of Bridgewater Promontory, and also to obtain some measure of the contribution of distant source rocks to the sands.

The opaque minerals comprise the greater part of nearly every concentrate other than those from the Bridgewater Promontory, where olivine is dominant, and the harbour floor samples, where augite predominates. Polished briquettes of selected concentrates show that the opaque minerals comprise ilmenite, maghemite, limonite and ferriferous rutile, with hematite rare. Associated with them are varying proportions of slag and rusted iron scale, and wherever the percentage of opaque minerals rises to over 70% of the heavy mineral concentrates this is due to an influx of heavy slag. Since the opaque minerals are partly of basaltic origin, partly of granitic and metamorphic origin, and partly due to artificial contamination by shipping activities, they have little bearing on the problem in hand and so have been grouped together in all of the grain counts.

Augite occurs characteristically as pale violet to grey angular fragments showing little sign of rounding. Its greatest concentration is in the harbour floor samples, where it comprises 50% to 65% of the total heavy minerals, and along the western part of Portland Bay where basaltic rocks are exposed in the sea cliffs. Here the augite comprises up to 48% of the heavy minerals. It is also a major constituent of the sands derived from material dumped on the shore adjacent to the Harbour Trust offices. Some of the augite grains in the Discovery Bay sands and in the sands from the eastern end of Portland Bay are pale green and somewhat rounded. They are probably not derived from the local basaltic rocks. The proportion of this green augite increases relative to the amount of pale violet augite derived from the basalts, in a north-westerly direction along Discovery Bay beach. The total amount of augite, however, is very small.

Olivine is present in the harbour beaches and harbour floor sands, but generally as a minor constituent only, the ratio of augite/olivine being from 10 : 1 up to 60 : 1. Close to exposed basalt, as in Descartes Bay, the proportion of olivine is much greater, with ratios of augite/olivine of 1 : 5, and on the Bridgewater Promontory beaches olivine constitutes 50% to 80% of the heavy minerals. The restriction of olivine in any abundance to the immediate vicinity of its source rocks probably arises from its chemical instability compared to augite, combined with its brittleness. A proportion of the olivine grains show partial alteration to serpentine. Occasionally both the olivine and augite occur embedded in volcanic glass, in the heavy mineral concentrates.

Zircon is the most abundant of the granitic minerals in the heavy mineral assemblages, being present also in all but two samples, these being No. 123, which contains 97·6% augite, olivine and opaque minerals, and No. 206 which contains 92% olivine. By contrast, the zircon forms upwards of 35% of the total heavy minerals in some of the Discovery Bay sands. The majority of the zircon grains are well rounded. Most are clear and colourless, a few are pale yellow, while pink and greenish-blue grains are rare. Some are fluorescent under a Mineralight.

Tourmaline is next in abundance to zircon among the granitic-metamorphic group of heavy minerals, and is present in all but the three samples Nos. 123, 125 and 206. It forms exceptionally well-rounded grains like some of the zircon, and has likewise probably survived more than one cycle of erosion. Brown varieties predominate, but there are yellow, green and blue grains as well, none of which are characteristic of any particular sand. As observed from Table 4, the tourmaline, like zircon and rutile and others of the granitic-metamorphic group, constitutes a distinctly greater proportion of the heavy mineral assemblages in the Discovery Bay sands than elsewhere, pointing to the Glenelg River as a possible source of supply. Most of these minerals are known to occur in rocks outcropping in the Casterton district 30 miles east-north-east of the Glenelg River mouth, and within its drainage area (Wells, 1956).

Garnet is uniformly present as rounded and sometimes sub-spherical pink to reddish-brown grains. Along Discovery Bay it rises to 3·5% of the total heavy minerals, but elsewhere is generally less than 1%.

Rutile constitutes less than 0·5% of the heavy minerals in the harbour beach and harbour floor sands but rises to as much as 3% on the eastern Portland Bay beaches. In the Discovery Bay sands it comprises 3% to 5% of the heavy minerals, and in the Bridgewater Promontory sands up to 2·5%.

Anatase and brookite are only sparingly represented in some assemblages, being absent from others. Hornblende occurs as green, greenish-blue and brownish-green varieties, accompanied by a little pale green to colourless actinolite. It is generally more common in the heavy minerals from the Discovery Bay sands than elsewhere. Andalusite comprises up to 2·5% of the total heavy minerals in Discovery Bay sands, but elsewhere makes up only 0·1% to 0·2%. Monazite, though present in three-quarters of the samples, is very sparse in the harbour beach and harbour floor sands. It has its maximum development along Discovery Bay and shows a distinct increase on the eastern compared with the western Portland Bay beaches. Staurolite shows a similar distribution, while cassiterite, cyanite, sillimanite, spinel and topaz show somewhat comparable trends in distribution to that of the monazite.

White mica, on the other hand, has its strongest development in the harbour floor and harbour beach sands; elsewhere it occurs only sporadically and is wanting from the foot of dune sands along Discovery Bay.

Other minerals observed in the heavy mineral assemblages, but in too few grains to be recorded in the statistical counts, are corundum in samples Nos. 11, 16, 17, 35, 40 and 308, sphene in sample No. 110 and biotite in sample No. 103.

Grain Size Variation

Two points emerge concerning the grain size of the heavy minerals:

(a) As with the sands generally, the heavy minerals in the harbour beach and harbour floor sands are decidedly finer-grained than the heavy minerals in sands from Discovery Bay, Bridgewater Bay and the eastern beaches of Portland Bay.

(b) The detrital olivine was mainly much coarser-grained originally than the granitic-metamorphic group of heavy minerals, and probably coarser than the augite. This is revealed in sand such as that from Descartes Bay, in which the +52 mesh fractions, in addition to the —52 mesh fractions, contain significant amounts of heavy minerals. Comparison of the two fractions in this sand (Table 49, Min. Rept. 622) reveal that (a) the +52 mesh fraction contains about four times the weight of heavy minerals in the —52 mesh fractions; (b) that olivine comprises more than 85% of the +52 mesh fraction compared with only 36% of the —52 mesh fraction; and (c) that most of the granitic-metamorphic group of heavy minerals are restricted to the —52 mesh fraction. The original coarseness of the olivine grains near to the source in the basaltic rocks emphasizes the rapidity with which it disappears from the beaches.

Relative Distribution of Basaltic and Granitic-metamorphic Group Heavy Minerals

The averages of the mineral compositions of the heavy concentrates from the several groups of sands, shown in Table 4, reveal that the heavy minerals of the granitic-metamorphic group predominate in the Discovery Bay sands, while basaltic minerals predominate in the Bridgewater Promontory sands (chiefly olivine) and in the Portland Harbour sands (chiefly augite). As shown by Table 5, basaltic minerals predominate in the Portland Bay sands west of the Surrey River mouth, but the granitic-metamorphic group of minerals assumes equal or greater abundance than the basaltic minerals in the section east of the Surrey River mouth.

The antipathetic relationships of the basaltic minerals and the granitic-metamorphic group, and the distances that the basaltic minerals have migrated from points of origin, are shown in Figs. 15, 17 and 18.

Although the basaltic minerals have migrated north-westwards for some 26 miles along Discovery Bay, the volume has been very small (Fig. 15B).

The extent of migration along Portland Bay (Fig. 15A) is less easily determined, because basalts outcrop along the cliffs as far as Dutton Way, and each of the several rivers entering the bay must contribute a quota of basaltic detritus to the sands. However, basaltic minerals have been traced to, and probably extend considerably beyond, the mouth of the Eumeralla River, in markedly greater volume than along Discovery Bay. This would indicate that there has been a stronger movement of sands eastwards than westwards.

Since the data represented in Figs. 15, 17A and 18A do not reveal whether the decline in the percentage of the granitic-metamorphic group minerals is relative or absolute in the presence of abundant basaltic minerals, the weight percentages in the various sands of (i) zircon and (ii) total granitic-metamorphic group heavy minerals have been calculated. The weight percentages were obtained by multiplying the percentage of these minerals in the various heavy mineral concentrates by their respective index numbers. The products, multipled by 100, are shown in Figs. 16, 17B and 18B.

These diagrams reveal that for Discovery Bay (Fig. 16B) the granitic-metamorphic heavy minerals average about 0·01% by weight of the sand over the greater length of the beach, increasing in amount sharply to the west of the Glenelg River mouth, and increasing or maintaining their volume in Descartes Bay, so that here the "flood" of basaltic heavy minerals merely masks a normal volume of granitic-metamorphic heavy minerals.

TABLE 5

Comparison of Range and Average Percentage by Count Values of —52 (B.S.S.) Mineral Species in the Heavy Mineral Assemblages of Portland Harbour Beach Sands and Eastern Portland Bay Beach Sands

Mineral Species	Portland Harbour Beach Sands W. & S.W. of Surrey River (Samples 103–110 and 123–128)		Portland Bay Beach Sands E. of Surrey River (Samples 111–122)	
	Range %	Average %	Range %	Average %
Anatase	Pr.	—	0–0·3	0·05
Andalusite	Pr.	—	0–0·6	0·2
Augite	11·8–47·7	36·8	4·1–33·6	16·4
Brookite	0	0	Pr.	—
Cassiterite	0–0·1	0·007	0–0·5	0·09
Cyanite	0–0·3	0·02	0–0·1	0·008
Dolomite	0–0·3	0·02	0–12·7	1·0
Epidote	0–0·1	0·007	0·3–1·6	0·7
Garnet	0–0·2	0·03	Pr.–1·8	0·7
Hornblende	0·1–0·6	0·2	0·2–1·6	0·8
Hypersthene	0–0·1	0·007	Pr.	—
Iddingsite	0–3·0	1·0	0–0·5	0·2
Leucoxene	0·3–1·8	1·2	1·0–5·0	2·4
Monazite	Pr.	—	0–0·5	0·2
Olivine	0·2–12·2	2·5	1·1–15·2	5·3
Opaque Minerals	47·1–80·0	55·8	43·1–74·3	58·8
Rutile	0–0·8	0·2	0·2–3·4	1·2
Sillimanite	Pr.	—	0–0·1	0·007
Spinel	0	0	0–0·2	0·03
Staurolite	0–0·3	0·03	0–0·5	0·2
Topaz	0–0·1	0·01	0–0·5	0·04
Tourmaline	0–0·4	0·2	0·3–2·1	1·0
White Mica	0–0·4	0·2	0–0·4	0·09
Zircon	0–3·8	1·7	0·9–31·7	10·4
Zoisite	0–0·3	0·02	0–0·5	0·2
INDEX NUMBER	0·006–0·67	0·09	0·003–0·23	0·06

(Pr. = Present in minute amounts only)

By contrast, in Portland Bay (Fig. 16A) there is a real reduction in the volume of granitic-metamorphic heavy minerals to almost insignificant amounts west of the Fitzroy River—i.e., in the harbour area proper—whereas east of the Fitzroy River these heavy minerals are about twice as abundant as along Discovery Bay. At the south-west end of Portland Bay, where Bridgewater Promontory occurs, the proportion of granitic-metamorphic heavy minerals increases again and, as can be seen from Fig. 17A, B, a parallel relationship has developed for the Bridgewater Promontory beaches. Here, in the exposed eastern beaches, the total weight of granitic-metamorphic heavy minerals is about the same as along Discovery Bay, but tends to be masked by a "flood" of basaltic heavy minerals. At the sheltered western end of Bridgewater Bay, however, there is an absolute reduction in the volume of granitic-metamorphic heavy minerals.

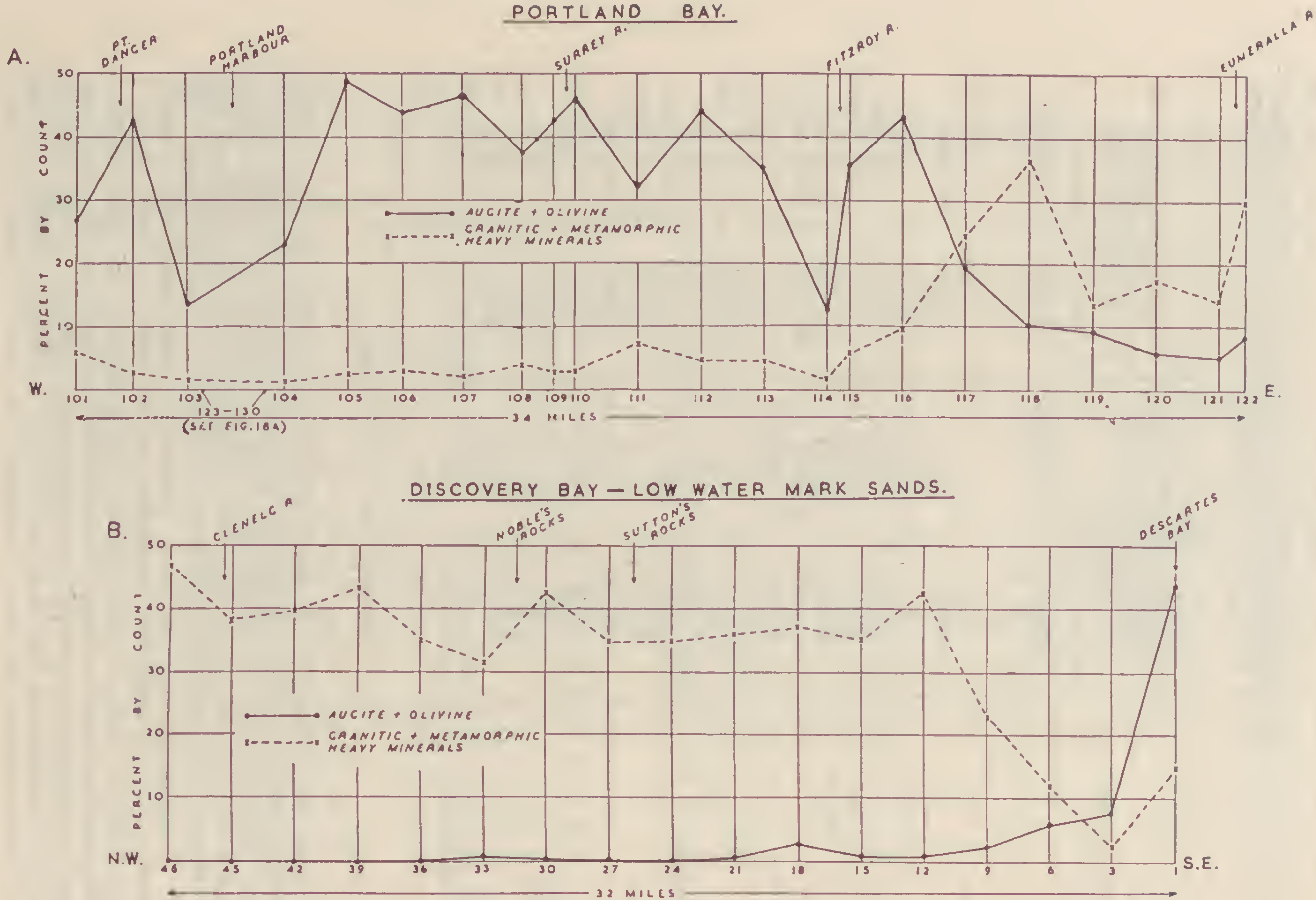

FIG. 15—Graphs comparing the percentage by count values of the —52 (B.S.S.) basaltic heavy minerals (augite and olivine) with those of the —52 (B.S.S.) granitic and metamorphic heavy minerals.

A—Portland Bay beach sands (samples 101-122).
B—Discovery Bay low water mark sands (samples 1-46).

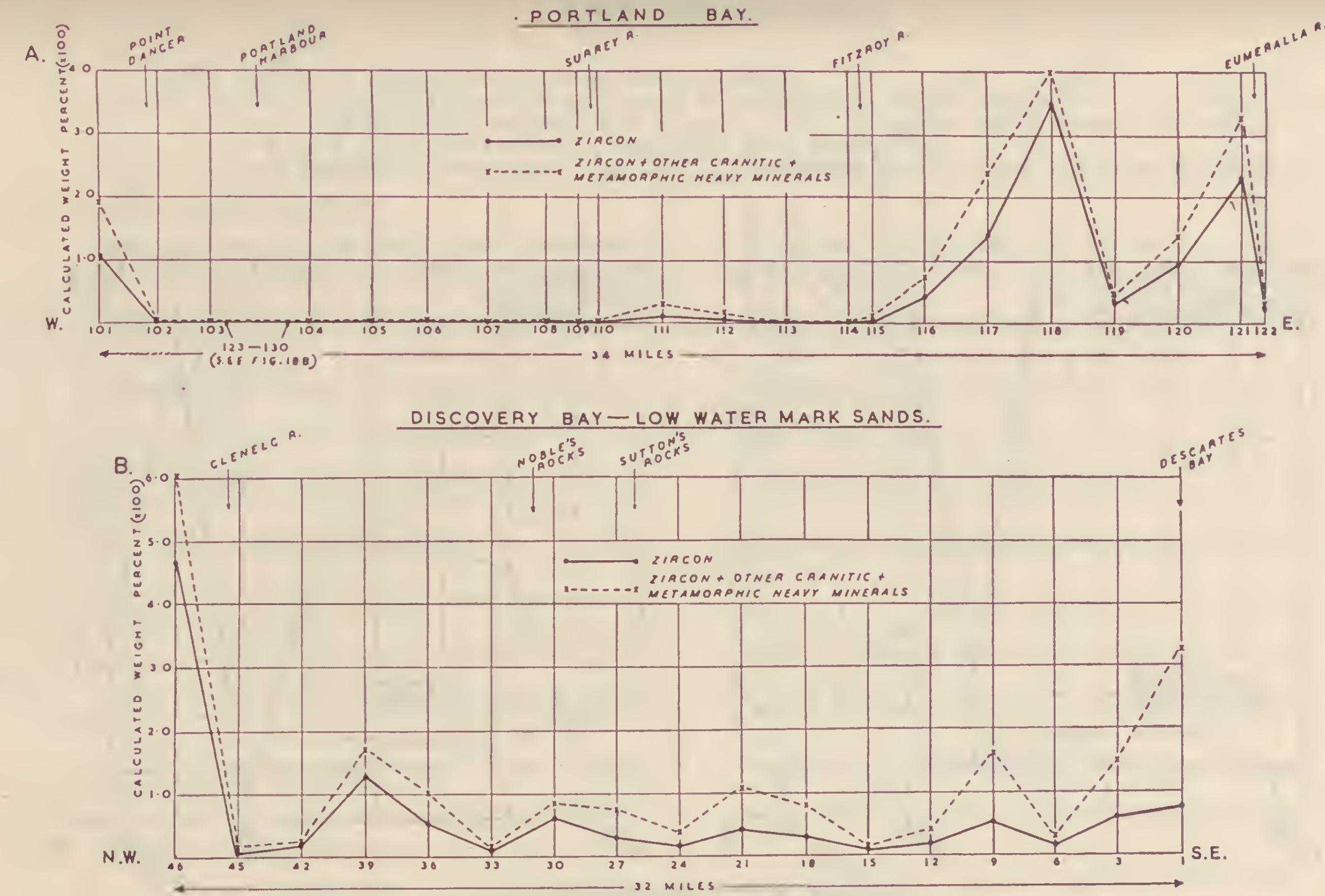

FIG. 16.—Graphs comparing the calculated weight percentage values (× 100) of the —52 (B.S.S.) zircon fraction with those of the —52 (B.S.S.) zircon plus other granitic and metamorphic heavy mineral content.

A—Portland Bay beach sands (samples 101-122). B—Discovery Bay low water mark sands (samples 1-46).

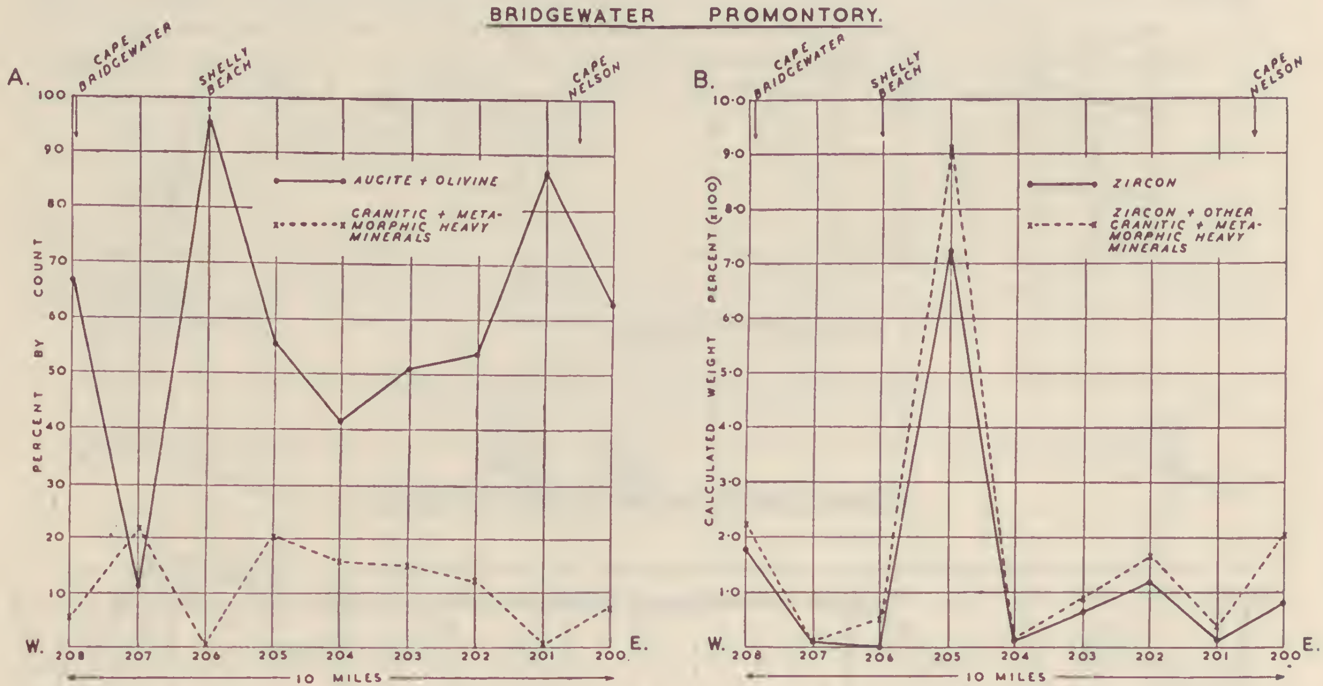

Fig. 17.—Graphs comparing—

A—the percentage by count values of the —52 (B.S.S.) basaltic minerals (augite and olivine) with those of the —52 (B.S.S.) granitic and metamorphic heavy minerals;

B—the calculated weight percentage values (× 100) of the —52 (B.S.S.) zircon fraction with those of the —52 (B.S.S.) zircon plus granitic and metamorphic heavy mineral content;

for the Bridgewater Promontory beach sands (samples 200-208).

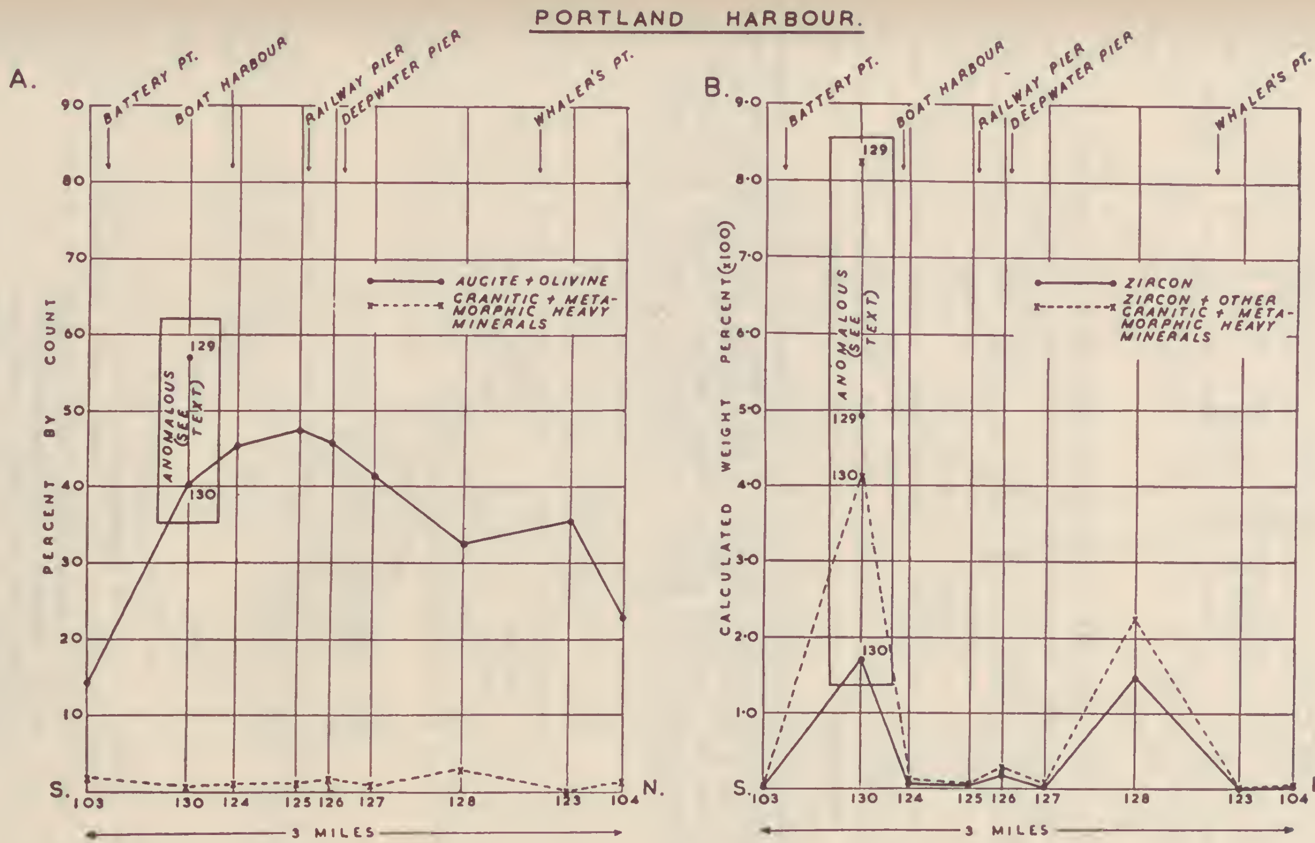

FIG. 18.—Graphs comparing—

A—the percentage by count values of the —52 (B.S.S.) basaltic heavy minerals (augite and olivine) with those of the —52 (B.S.S.) granitic and metamorphic heavy minerals;
B—the calculated weight percentage values (× 100) of the —52 (B.S.S.) zircon fraction with those of the —52 (B.S.S.) zircon plus other granitic and metamorphic heavy mineral content;
for the Portland Harbour beach sands (samples 103, 104 and 123-130).

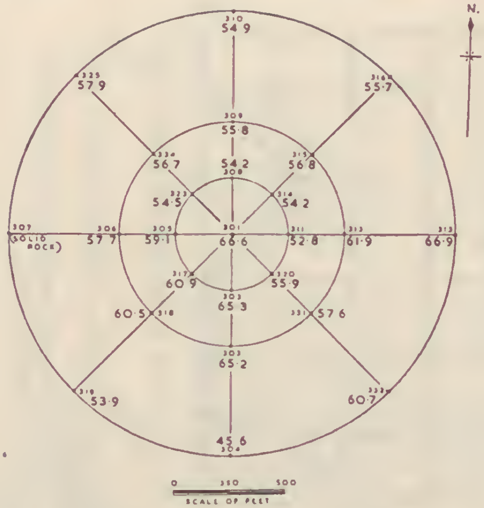

FIG. 19.—Diagram showing small variations of the percentage by count values of the —52 (B.S.S.) basaltic heavy minerals (augite and olivine) in the Portland Harbour floor sands (samples 301-325). (Smaller figures represent locations of samples; larger figures represent percentage by count values).

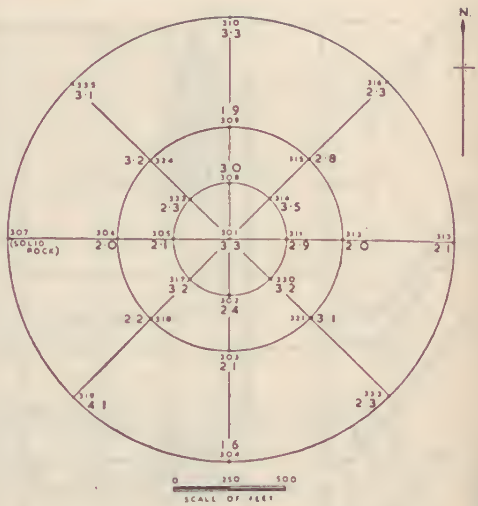

FIG. 20.—Diagram showing small variations of the percentage by count values of the —52 (B.S.S.) granitic and metamorphic heavy minerals in the Portland Harbour floor sands (samples 301-325). (Smaller figures represent locations of samples; larger figures represent percentage by count values).

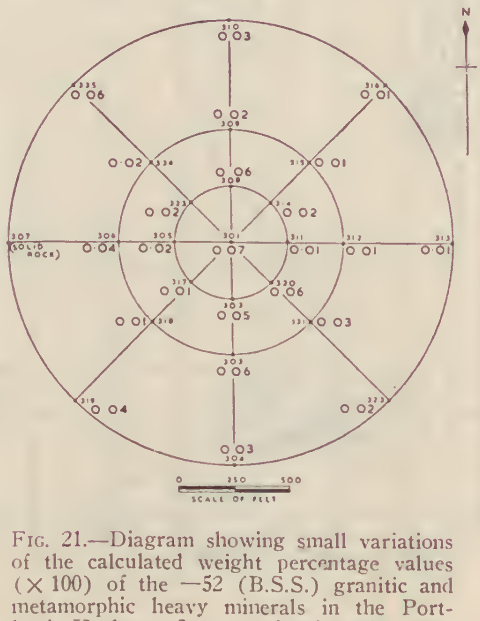

FIG. 21.—Diagram showing small variations of the calculated weight percentage values (× 100) of the —52 (B.S.S.) granitic and metamorphic heavy minerals in the Portland Harbour floor sands (samples 301-325). (Smaller figures represent locations of samples; larger figures represent calculated weight percentages).

From place to place within the 2000 ft. diameter sampling area on the harbour floor there is little significant variation in amount of either (a) the basaltic heavy minerals (Fig. 19) or of the granitic-metamorphic heavy minerals (Fig. 20). No marked trends are revealed among these minor variations. The calculated weight percentages of the granitic-metamorphic heavy minerals (Fig. 21) reveal considerably smaller proportions of this group of minerals than elsewhere in the Portland sands.

Mineral Ratios

The significance of the variations in the total amounts of the granitic-metamorphic heavy minerals present in the Portland sands becomes evident from a consideration of Tables 6 and 7. The relative abundances of the principal heavy minerals with respect to each other in the various sands have been expressed in Tables 6 and 7 as the ratios of their average percentages. These ratios reveal an interesting difference between the unstable basaltic heavy minerals and the highly stable granitic-metamorphic heavy minerals. The basaltic heavy minerals show extreme variation in their ratios (Table 6) because the supply is continually being renewed at some points, while destruction proceeds rapidly during transport. On the other hand, the granitic-metamorphic heavy minerals, being very stable, are capable of persisting through several cycles of erosion, transportation and sedimentation, and they show a relative constancy of ratios (Table 7), pointing to an established equilibrium. It is therefore deduced that weight of granitic-metamorphic heavy minerals in any given sand is an approximate measure of the total volume of minerals of all sorts of granitic-metamorphic origin in that sand. This finds confirmation in the general sympathetic variation of total insoluble material and granitic-metamorphic heavy mineral content in the various sands.

The fact that the sands in the sheltered sections of the coastline—viz., the Portland Harbour area and the western end of Bridgewater Bay—show an absolute reduction in content of granitic-metamorphic heavy minerals compared with the sands from the more exposed beaches thus provides evidence that sand of granitic-metamorphic origin is not reaching these sheltered sections to the same degree as it is reaching the exposed sections. If the sand is migrating, then it is by-passing the sheltered areas in large measure. The distinctly finer grain size of the granitic-metamorphic heavy minerals and the low insoluble residues in these sheltered areas provide further confirmation of this conclusion.

Light Fraction Analyses

The fractions of the insoluble residues that floated in bromoform of sp. gr. 2·86 were examined microscopically as to composition, degree of rounding and extent of polishing. The light fractions are composed of mineral grains, insoluble organic matter and artificial substances.

Minerals

Quartz grains form the bulk of the light insoluble fractions in each size fraction. Much of the quartz is colourless and crystal clear, and is evidently derived from granitic and metamorphic rocks. Some is milky or white vein quartz, and there are small proportions of citrine, rose quartz and pale bluish coloured quartz. The coarser grains (+52 mesh) are usually much better rounded than the finer grains (—52 mesh) which are sub-rounded to sub-angular. A small proportion of the finer grains (—200 mesh) are sharply angular and often have conchoidal fracture sur-

TABLE 6

Ratios of Average Percentages by Count of Basaltic and other Mineral Species in the Heavy Mineral (—52 B.S.S.) Assemblages of the several groups of the Portland Sands

Group Number	Location	I	II	III	IV	V	VI	VII
		Olivine: Augite	Olivine: Zircon	Olivine: Rutile	Olivine: Tourmaline	Augite: Zircon	Augite: Rutile	Augite: Tourmaline
1	Discovery Bay, Low Water Mark Sands	1·80	0·15	0·80	0·63	0·08	0·45	0·35
2	Discovery Bay, High Water Mark Sands	1·30	0·07	0·47	0·26	0·05	0·37	0·21
3	Discovery Bay Foot of Dunes Sands	0·40	0·01	0·08	0·08	0·03	0·19	0·19
4	Bridgewater Promontory Beach Sands	10·20	6·40	48·30	106·20	0·63	4·70	10·40
5	Portland Bay Beach Sands	0·15	0·57	4·80	5·43	3·70	31·10	35·60
6	Portland Harbour Beach Sands (Natural)	0·12	4·50	64·30	45·00	36·80	525·70	368·00
7	Portland Harbour Beach Sands (Dumped Material)	0·09	7·30	—	7·30	156·10	—	156·10
8	Portland Harbour Floor Sands	0·05	1·90	8·30	6·25	42·60	184·70	138·50

TABLE 7

Ratios of Average Percentages by Count of Zircon to other Mineral Species in the Heavy Mineral (—52 B.S.S.) Assemblages of the several groups of the Portland Sands

Group Number	Location	I	II	III	IV	V	VI	VII
		Zircon: Rutile	Zircon: Garnet	Zircon: Hornblende	Zircon: Tourmaline	Zircon: Monazite	Zircon: Leucoxene	Zircon: Epidote
1	Discovery Bay, Low Water Mark Sands	5·3	10·3	6·4	4·3	26·6	3·9	7·8
2	Discovery Bay, High Water Mark Sands	7·1	12·6	19·5	4·1	26·9	6·5	19·5
3	Discovery Bay, Foot of Dunes Sands	6·3	13·4	17·5	6·3	25·9	7·6	18·9
4	Bridgewater Promontory Beach Sands	7·5	16·6	20·8	16·6	41·5	6·9	41·5
5	Portland Bay Beach Sands	8·4	16·7	11·2	9·6	74·4	3·5	16·8
6	Portland Harbour Beach Sands (Natural)	14·3	33·3	10·0	10·0	—	0·8	—
7	Portland Harbour Beach Sands (Dumped Material)	—	—	6·0	1·0	—	1·0	—
8	Portland Harbour Floor Sands	4·3	6·8	1·3	3·3	43·3	1·9	3·3

faces indicating relatively recent fracture. It is likely that the bulk of the quartz originated as grains coarser than +52 mesh, and that most of the finer grains owe their sub-rounded to sub-angular shape to fracturing of larger grains during transport. Many of the grains have frosted surfaces, others are well polished. Polished grains are most common in the Bridgewater Promontory and Discovery Bay sands.

Occasional grains of felspar (largely of basaltic origin), small clay pellets (mostly representing kaolinized felspar), rare flakes of muscovite, and occasional fragments of chert, flint, quartzite, reddish jasper and chalcedony also form a small proportion of the light mineral fraction.

A few granules of fresh and weathered glauconite and occasional casts after foraminifera are also encountered in some of the light mineral fractions. The glauconite is of authigenic origin.

Weathered fragments of basalt and fragments of fresher felspar-rich basalt occur among the light minerals in the Bridgewater Promontory beach sands and in some of the sands from the harbour area.

Organic Substances

The light insoluble fractions contain subordinate amounts of the spicules of silicisponges, chitin from horny sponges and crustacean carapaces, acid-resistant shells of certain foraminifera, a few coprolites, fragments of a soft marine fat or wax (adipocere), seaweed, capsules of terrestrial seeds and splinters of wood. These substances appear more commonly in the harbour floor sands than on the beaches.

Artificial Substances

The beaches and harbour floor sands are contaminated with a variety of small amounts of artificial substances which include slag, "slag-bombs", "smoke-bombs", boiler scale, rusted iron scale, glass fragments, electric light bulb fragments, chalky substances, plaster of Paris, charcoal, caulking pitch or bitumen, chips of coloured paint, brick-dust and fragments of cement. Small fragments of coal are also present on the harbour floor.

Brown and colourless bottle glass occurs in many of the sands, particularly in the harbour beach sands, as angular to rounded fragments that are often frosted.

Slag occurs in considerable concentrations in such places as Descartes Bay (samples Nos. 1 and 2) and several parts of Portland Bay. Sometimes it is sufficiently heavy to sink with the heavy minerals on bromoform separation. It occurs chiefly as angular, bubble-pitted fragments of various colours, and is sometimes vitreous, occasionally porcellanous. The "smoke-bombs" are clear yellowish-green to green and colourless sub-spherical glass bodies that form from the fly-ash in the funnels of coal-burning steamships and railway engines; they are represented in both the +52 and —52 mesh size fractions. "Slag-bombs" are similar but opaque and porcellanous; dark brown and black varieties are usually magnetic.

These artificial contaminants are present in places in significant amounts. Thus in sample No. 106 from near the western end of Portland Bay 40% of the +52 mesh insoluble matter consisted of slag, while in No. 108 there was 8% of slag. The total insoluble matter in these sands was 9·2% and 6·6% respectively.

Notable concentrations of slag in the coarser fractions of the sands along the eastern section of Portland Bay (samples Nos. 111, 114, 121 and 123) indicate a tendency for it to be carried in from the south-west, by-passing the harbour area proper. A comparable drift of slag is also noted in Descartes Bay at the eastern end of Discovery Bay.

Thickness of Sand in Harbour

The thickness of sand in the Portland Harbour area ranges from the merest veneer on a rock floor of basalt or limestone to a thickness of several feet. Data supplied by the Portland Harbour Trust Commission indicate that in the area of the proposed turning circle the sand cover is from 6 to 12 ft. thick, with a floor of clay and limestone beneath.

Two observations are of interest in this connection. Firstly, it has been recorded that coarse boulders of basalt were recovered by divers working at the outer end of the long pier (Main or Deepwater Pier) in the harbour (Coulson, 1941, p. 399), and the highly basaltic nature of the material dredged from the Boat Harbour (samples Nos. 129 and 130) suggests proximity to basaltic rock bottom in this section of the harbour also. Secondly, one of the samples taken by grab from the harbour floor (sample No. 307) consisted of compact sandstone of coarser grain size than that of the harbour floor sands in the vicinity. A thin section of this sandstone revealed it to be micaceous arenite composed of sub-angular to sub-rounded quartz grains from 0·02 to 1·0 mm. across, cemented together by well defined quartz overgrowths, and a proportion of fine-grained sericitic matrix. In addition, there are occasional coarse flakes of muscovite and well-rounded grains of zircon, rutile, tourmaline, garnet and black oxide minerals, together with a few fragments of quartzite. The heavy minerals in the sandstone are distinctly coarser in grain size than those in the sands on the harbour floor.

Movement of Marker Minerals

Tracing the movement of the marker minerals added to the sea floor at two points and at low water mark on three well-separated beaches in the Portland district followed the detailed mineralogical examination of the beach and harbour floor sands, and constituted the second stage of littoral drift studies in this region.

Marker Minerals

The choice of marker minerals was limited by a variety of factors, namely:

(1) In view of the relatively small tonnage of marker minerals that could be introduced at any given point, it was obvious that the marker mineral, as it migrated, would become widely dispersed through a vastly greater volume of sand. It was therefore necessary to select minerals with distinctive properties, so that they could be easily concentrated in a minimum of time, and be readily recognized even when present in the most minute amounts.

(2) It was equally necessary to select minerals not already in the sands in minute quantities. This rendered essential the preliminary, very detailed study of the mineral composition of the sands along the 90 miles of coastline involved in the littoral drift studies (Min. Rept. 622). None of the 42 minerals found in the sands, nor any of the artificial products present in them, could be used.

(3) It was necessary to select minerals that could be purchased readily in amounts of 5 to 20 tons in a fairly pure form, in a suitably finely divided state and at a reasonable cost.

The minerals selected were:

Pyrite—in the form of pyritic concentrates from the Norseman Mine, W.A., as supplied for the manufacture of sulphuric acid. Such pyrite is all —52 mesh and occurs as bright, brassy-yellow angular particles of specific gravity about 5.

Red-pyrite-cinders—a residue product from the roasting of pyrite concentrates. It consists of red angular particles of magnetic iron oxide, with a specific gravity about 4.

Brown garnet (*andradite*)—occurring as a major component of the gravity tailings from the ore of the King Island scheelite mine, in which it occurs as brown isotropic angular particles. It is readily distinguished from the pink to pale red garnet occurring in small quantities in the Portland sands, and has a specific gravity of 4, which distinguishes it, among other properties, from brown bottle glass in the sands.

Red rutile—in the form of rutile concentrate produced from heavy beach sands at Stradbroke Island, Queensland. This rutile is a deep red colour, much coarser than and quite distinct from the paler pinkish and honey-yellow to brown rutile that occurs in the sands at Portland. It is well-rounded and has a specific gravity of about 4·5.

Limits of Detection

Each of these minerals is readily distinguished under the microscope from the naturally occurring minerals in the sands, and because of relatively high specific gravity values each is readily and quickly concentrated when sand containing it is treated on a Haultain Superpanner.

Thus a test product prepared by adding 0·001 gm. of the pyrite concentrate to a 50 gm. sample of the naturally occurring pyrite-free sand from Henty Beach, when treated on the Superpanner, yielded a "head" containing 625 grains of pyrite among the naturally present heavy minerals.

625 grains of pyrite = 1 part of pyrite in 50,000 parts of sand,

so that—

> 1 grain of pyrite in the Superpanner head from 50 grams of sand = 1 part by weight of pyrite in 31,250,000 parts of sand (i.e., approximately 3 parts per 100,000,000).

Some of the samples of sand tested while following the movement of the pyrite yielded Superpanner "heads" containing as few as 2 grains of pyrite per 50 gram sample, equivalent to about 5 parts by weight of pyrite per 100,000,000 parts of sand.

The other marker minerals could be detected when present in approximately the same minute amounts.*

Testing Programme

Five tests were made, using marker minerals, to trace the movements of sands:

(A) Twenty tons of *pyrite* concentrates were dumped at low water mark at Descartes Bay at the eastern end of Discovery Bay on June 1st, 1955.

- (i) Samples were then taken at low water mark once a week at intervals of 100 yards north-west and south-east of the dumping site, new stations being established further from the dump as the pyrite progressed along the beach. After a period of nine weeks, the distance between successive stations to the north-west was increased to quarter-mile intervals, and after twelve weeks to half-mile intervals.
- (ii) Samples were taken at monthly intervals at the most westerly beach in Bridgewater Bay, and at Shelly Beach in Bridgewater Bay.
- (iii) When the pyrite reached the south-eastern extremity of the beach, samples were taken at White's Beach, three-quarters of a mile south-easterly from the dump.

*It is stressed that the Superpanner is not a precise instrument in that each run is subject to slight variations in control manipulation by the operator.

(B) Five tons of *garnet-rich* tailings from the King Island scheelite mill were dumped at low water mark on Narrawong Beach on June 6th, 1955. Samples were taken once a week at intervals of 100 yards east and west of the dump site, new stations being established as the garnet progressed along the beach.

(C) Twenty tons of *red-pyrite-cinders* were dumped on the sea floor between Lawrence Rocks and Point Danger on June 21st, 1955. Samples were taken at low water mark at monthly intervals from the beaches at Nelson Bay, Grant Bay, Quarry Bay and Lady Bay.

(D) Five tons of *red rutile* were dumped at low water mark at the sea wall midway between Railway Pier and Deepwater Pier on June 29th, 1955. Samples were taken at three- to four-day intervals from the sea floor at intervals of 250 yards directly offshore from the dump, on a line normal to the strand-line. New stations were established as the rutile progressed seawards. Subsequently the sampling was reduced to weekly samples.

(E) Ten tons of *pyrite* concentrates were dumped on the harbour floor at the point of intersection of the Main Breakwater reference line and a centre line on Julia Street, Portland, on July 4th, 1955. Samples were taken at first daily and later at three- to four-day intervals at stations spaced at intervals of 250 feet along the NW, NE, SW and SE compass bearings from the dump site.

More than 200 samples were examined. Each was treated on a Haultain Superpanner to concentrate any marker mineral present along with the natural heavy mineral content. The Superpanner "head" concentrate was then examined under a binocular microscope at a magnification of 72, for the presence of marker minerals.

Pyrite in Discovery Bay

The pyrite dumped on Discovery Bay beach near the southern end of Descartes Bay migrated along the coast both to the north-west and to the south-east (Fig. 22).

North-westerly movement. The progress of the pyrite in a north-westerly direction is shown in Fig. 23. When the testing was stopped after a period of 97 days, the pyrite had reached a station four miles north-west of the dumping site. As can be seen from Fig. 23, it had moved at a fairly steady rate of about one mile in 25 days, or 70 yards a day. The concentration of pyrite detected at any one sampling station did not exceed 1 part in 830,000 parts of sand, and the concentration at the four-mile station was 1 in 7,500,000.*

South-easterly movement. The movement of the pyrite in a south-easterly direction was initially much slower. It took 17 days to move 200 yards from the dump, and 42 days to move 500 yards—an average rate of 12 yards a day, about one-sixth of the speed of movement to the north-west.

Beyond this point it entered on the rocky coastline of the Bridgewater Promontory, and its rate of movement rose sharply. Fifty-six days after dumping it was detected on White's Beach, the most south-easterly patch of sand on the western side of the Promontory and three-quarters of a mile from the dumping site; in a sample taken at this beach 59 days after the dumping, it was present in the concentration of 1 part in 50,000. This was the overall concentration in a 5,000-gram

*All concentration figures are based on the number of grains of pyrite observed by microscopical examination of the Superpanner "head" from a 50-gram sample of the —52 mesh fraction of the sand in each sample.

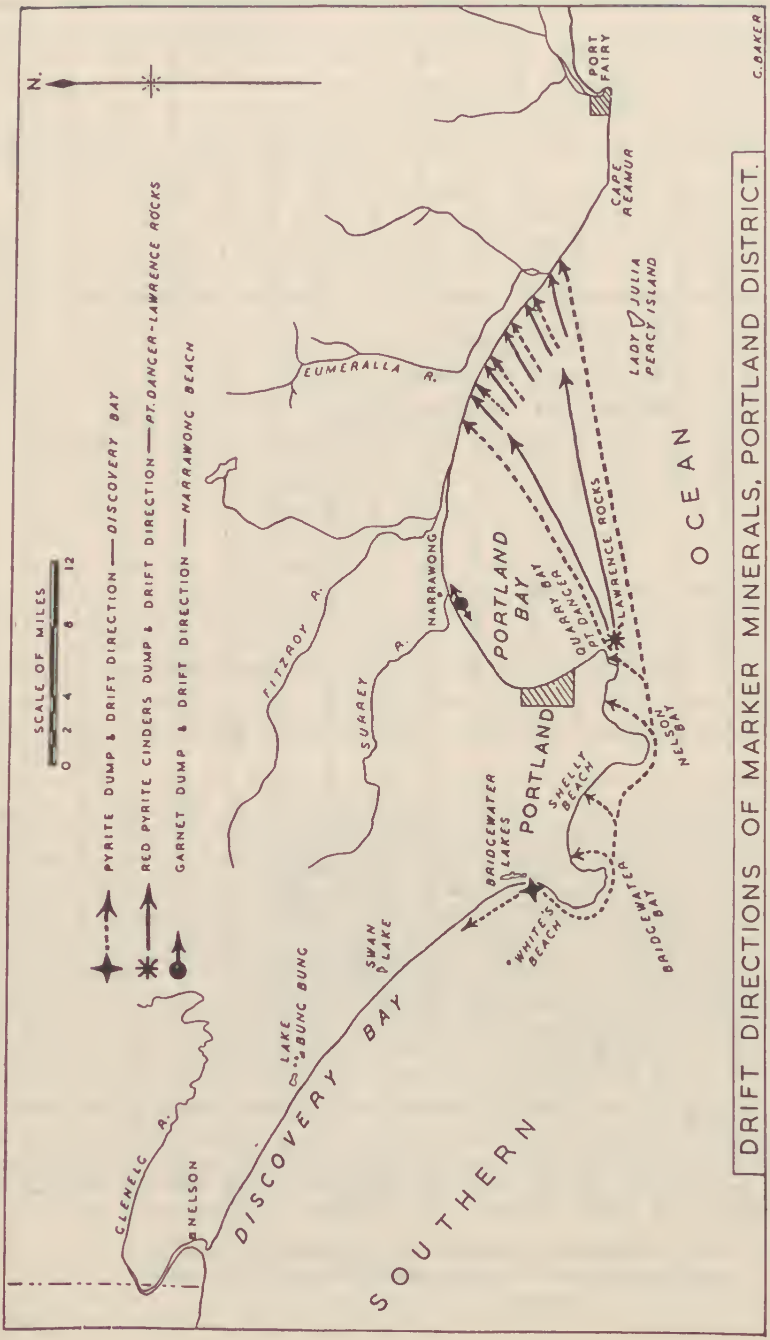

FIG. 22.—Sketch map of the Portland District showing direction of drift of (1) pyrite from the dump on Discovery Bay beach, (2) brown garnet from the King Island scheelite tailings dump on Narrawong Beach, and (3) red-pyrite-cinders from the dump on the sea floor between Point Danger and Lawrence Rocks.

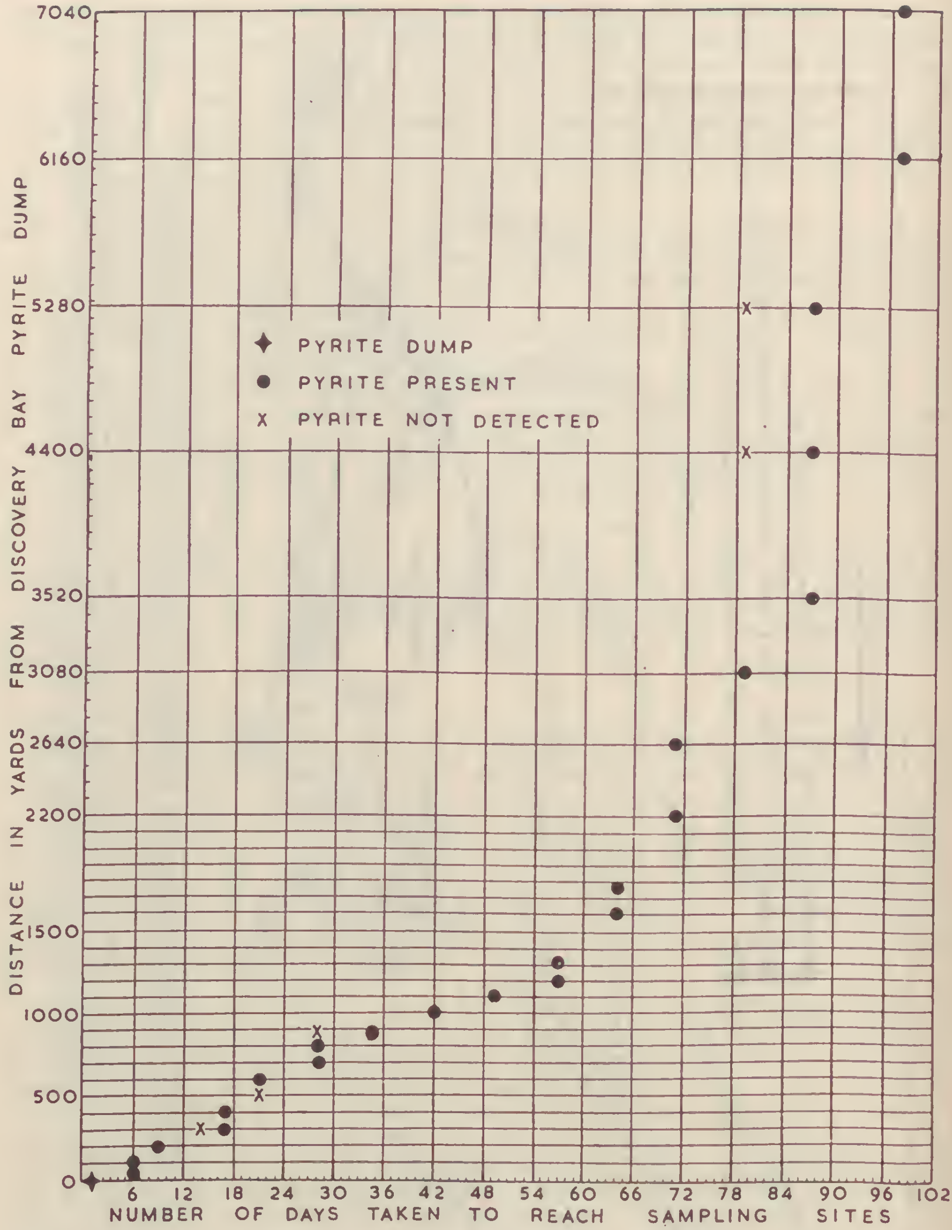

FIG. 23.—Graph showing the distance (in yards) and the time (in days) of north-westerly drift of pyrite along Discovery Bay beach.

sample representing all fractions of the relatively coarse sand occurring at this locality, and was the highest concentration of marker mineral observed at any sampling station. It is evident that the rate of movement of the pyrite had increased significantly after leaving the sandy section of Descartes Bay, and that it had accelerated from 12 yards a day to not less than 60 yards a day. In fact, it had moved considerably faster than this, and had passed the end of Cape Bridgewater before it was detected at White's Beach.

The first monthly samples taken at Bridgewater Bay and Shelly Beach, 31 days after the dumping, failed to yield any trace of pyrite, but the first sample taken at Nelson Bay 50 days after the pyrite had been dumped on Discovery Bay beach revealed a concentration of pyrite of 1 part in 7,500,000. The Nelson Bay sampling station was established primarily to test the movement of red-pyrite-cinders from near Lawrence Rocks, and the first sample was taken there a month after the red-pyrite-cinders were dumped. The second series of monthly samples in Bridgewater Bay and at Shelly Beach, taken 64 days after the dumping of the pyrite, both revealed pyrite. In Bridgewater Bay beach sand, it was present in the proportion of 1 part in 10,000,000, and at Shelly Beach in the proportion of 1 part in 4,000,000. At the third sampling, after 89 days, the concentration in Bridgewater Bay had increased to 1 part in 2,500,000 and at Shelly Beach to 1 part in 2,000,000.

At Nelson Bay the concentration showed no change at 81 days after dumping, but had increased to 1 part in 4,500,000 after 92 days.

On the evidence, this accelerated movement developed after the 42nd day of the test, and in the following eight or nine days the pyrite travelled about 18 miles (sea distance) ; that is, at a rate of not less than two miles per day. After turning Cape Bridgewater, it showed a tendency to partly by-pass Bridgewater Bay proper, and headed north-eastwards for Shelly Beach and Nelson Bay. It is probable that it moved more rapidly when travelling eastwards or north-eastwards after rounding Cape Bridgewater than when moving southwards from Descartes Bay to Cape Bridgewater.

The pyrite continued to move rapidly eastwards and north-eastwards, and was detected in the sands of Grant Bay, three-quarters of a mile south-west of Point Danger (see Fig. 22) in a concentration of 1 part in 15,500,000 for the first time in a sample taken 125 days after it had been dumped on Discovery Bay beach.

Prior to this, however, it had reached the beaches on the eastern side of Portland Bay, a distance by sea of some 42 miles from the original dump. A series of samples taken between the mouths of the Fitzroy and Eumeralla Rivers, to test the possible drift of red-pyrite-cinders in this direction, revealed that this substance, as well as the pyrite, had reached this section of the coast. The samples were taken 105 days after initial dumping of the pyrite on Discovery Bay beach. The average concentration in six samples taken at low tide mark at two-mile intervals along the eastern coast of Portland Bay was 1 part in 4,500,000.

Concurrent tests on samples from pocket beaches on the western side of Portland Bay revealed no trace of the red-pyrite-cinders from Lawrence Rocks, and only a sporadic grain or two of pyrite, equivalent to concentrations of the order of 1 part per 100,000,000 (one particle of pyrite obtained from 150 grams of sand).

It is thus evident that the bulk of the pyrite by-passed Portland Harbour, and to a lesser extent by-passed Bridgewater Bay and Grant Bay, as it moved eastwards and north-eastwards from Cape Bridgewater. It travelled about 42 miles (sea distance) in not more than 105 days, and if allowance is made for the slow start of 500 yards in 42 days, then it moved the 42 miles in not more than 63 days, giving a minimum average speed of one mile in 1.5 days. Such figures are very approximate, but they are helpful in comparing behaviour of the marker minerals at the several testing sites.

Red-pyrite-cinders from Lawrence Rocks Area

The movement of the red-pyrite-cinders from the dump on the sea floor between Lawrence Rocks and Point Danger is shown in Fig. 22.

Sampling stations were established at Nelson Bay, Grant Bay (between Cape Grant and Point Danger), Quarry Bay and Lady Bay in the expectation that the red-pyrite-cinders would migrate westwards, north-westwards or northwards, but successive samples at each of these sites failed to yield any trace of the red-pyrite-cinders. However, when pyrite was detected in samples from Bridgewater Bay, Shelly Beach and Nelson Bay it was concluded that the red-pyrite-cinders were most probably moving eastwards.

Accordingly, it was arranged that samples should be taken along the eastern side of Portland Bay, between the mouths of the Fitzroy and Eumeralla Rivers, at original sampling stations 116, 117, 118, 119, 120 and 122, where the sands had been examined during stage I of the littoral drift investigations (Mineragraphic Report No. 622, Fig. 1). These samples were taken 82 days after the dumping of the red-pyrite-cinders, and each sample yielded a few distinctive grains of the magnetic red-pyrite-cinders, together with a few grains of pyrite, the two being present in about the same proportions in each sand sample. The sample from station 122, east of the Eumeralla River mouth, contained fewer grains of both red-pyrite-cinders and pyrite than the others.

Since no trace of the red-pyrite-cinders has been found in the harbour floor sands, and none in the beach sands from the western side of the harbour, it is evident that the movement of the red-pyrite-cinders has been essentially north-eastwards across the mouth of Portland Bay, and not into the Bay. It moved 20 miles north-eastwards with a minimum average rate of movement of one mile in four days. In all probability the rate of movement was considerably faster, since the Discovery Bay pyrite travelled 42 miles in 105 days or less (possibly even less than 63 days) to reach the same beach section.

Garnet (Andradite) on Narrawong Beach

In sharp contrast to the pyrite at Discovery Bay and the red-pyrite-cinders at Lawrence Rocks, the garnet (andradite) dumped in the form of tailings from the King Island scheelite mine on to the site at Narrawong Beach (Fig. 22) moved extremely slowly both eastwards and westwards from the dump. The progress in each direction is shown in Fig. 24, from which it is evident that over a period of 92 days the garnet migrated 400 yards to the west at a rate of about four yards per day, and 600 yards to the east at a rate of about six yards per day. For the first 30 days of the test the rate of movement was slower, and approximately equal in both directions. The concentration of the garnet was low, never exceeding 1 part in 4,000,000.

Ninety-five days after the dumping a sample was taken from the sea floor 250 yards south of the dumping site, to check on the possibility of seaward migration, but no brown garnet was detected in this sample.

Rutile at the Sea Wall, between the Piers

Beach level at the short section of sea wall between Deepwater Pier and Railway Pier in Portland Harbour rises and falls irregularly, with a tendency to fall during the winter and rise in the summer. To test the extent of movement of the sand

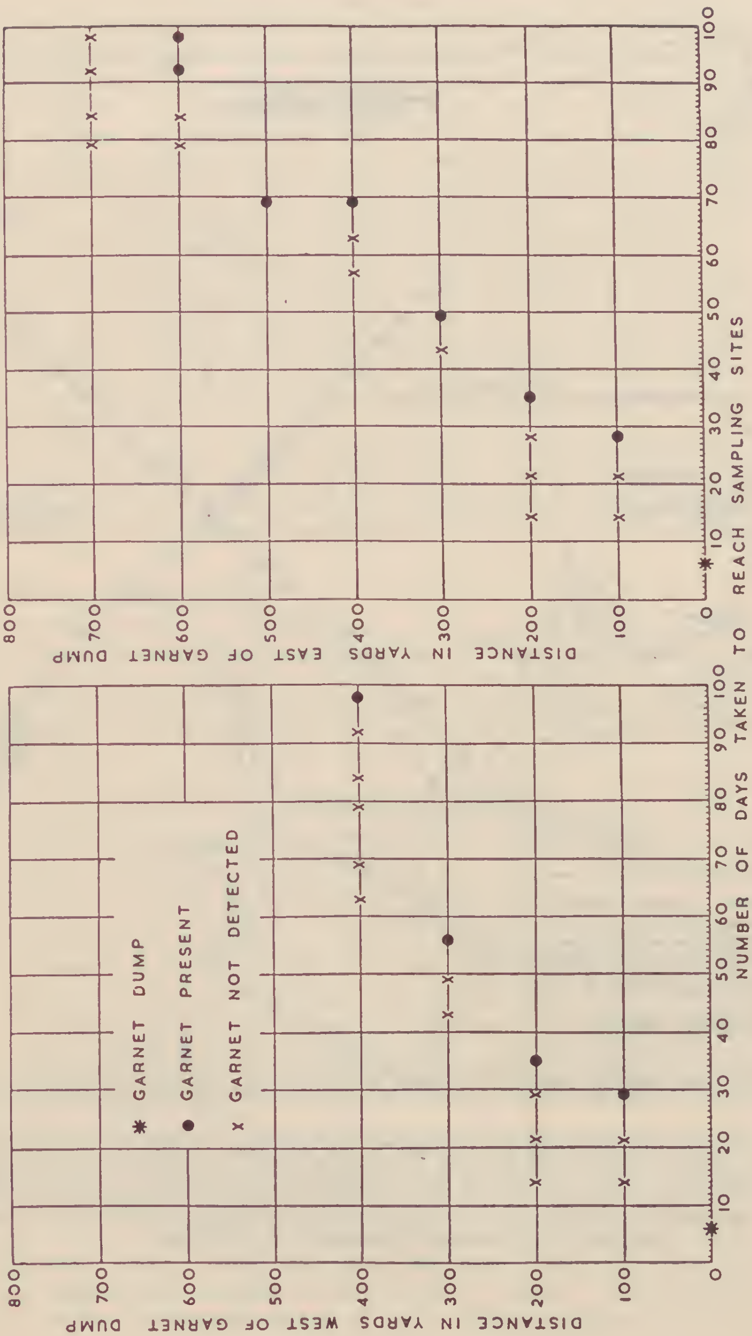

FIG. 24.—Graph showing the distance (in yards) and the time (in days) of westerly and easterly drift of brown garnet along Narrawong Beach, Portland Bay.

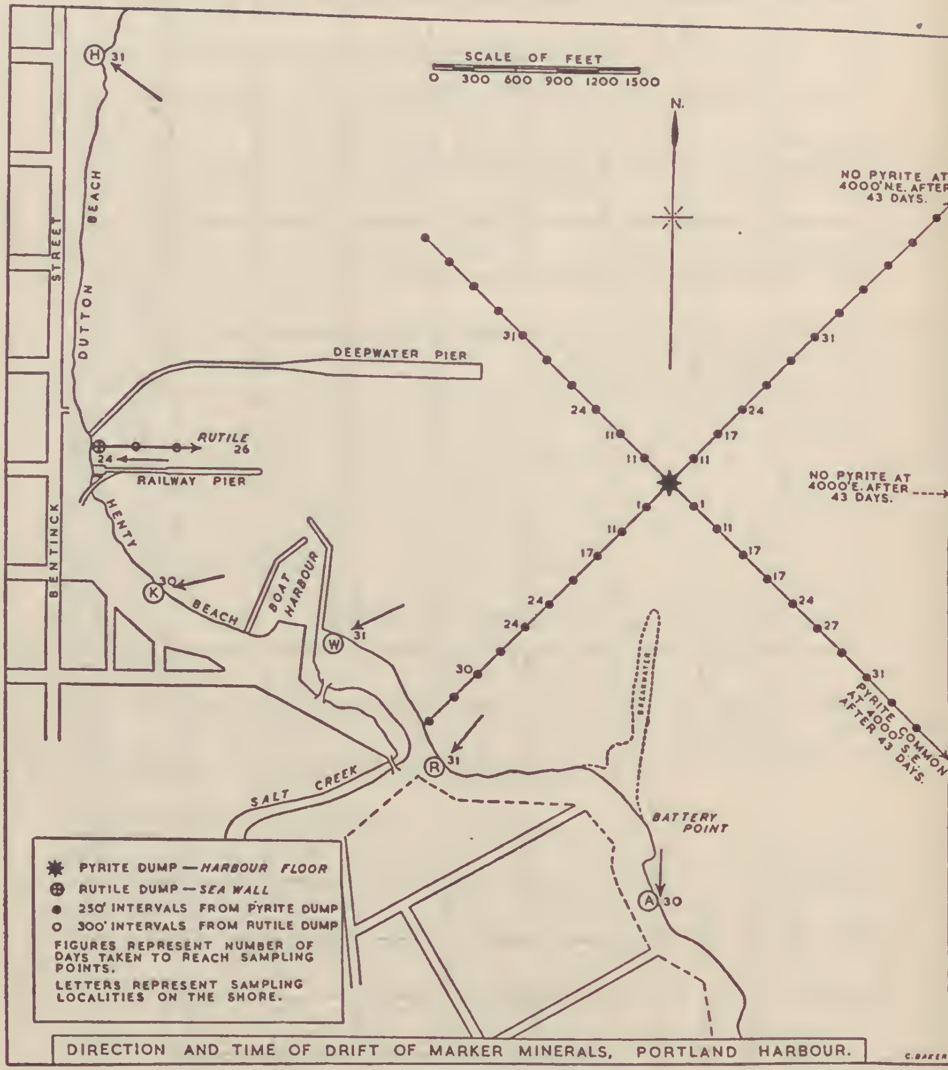

FIG. 25.—Sketch map of Portland Harbour showing directions, distances (in feet) and times (in days) of (1) the seaward drift of rutile from the sea wall between Railway Pier and Deepwater Pier, and (2) the drift of pyrite over the harbour floor from the dump at the point of intersection of the Main Breakwater reference line and a centre line on Julia Street and Railway Pier, Portland.

out on to the harbour floor when beach level was reduced, a dump of rutile was established at this point (Fig. 25). Its movement has been very slow. Rutile first appeared on the sea floor at the sampling station 250 yards east (directly offshore) from the dump site in the eleventh sample taken at this point, 26 days after dumping. The concentration of rutile in this sample was 1 part in 7,500,000; in the twelfth sample, taken at this station three days later, the concentration of the rutile had increased slightly. After a period of 127 days, the rutile had not appeared at the 500-yard sampling station, nor at the 750-yard sampling station, but a small amount (1 part in 10 million) was present at the 500-yard station 146 days after dumping, and a lesser amount (1 part in 15 million) at the 750-yard station.

A check for lateral movement of the rutile, made 32 days after the dump was established, revealed a concentration of 1 part in 300,000 on the dump site, 1 part in 1,500,000 at a point 100 yards south of the dump, and 1 part in 3,000,000 at a point 100 yards north of the dump. Samples taken at various points along the harbour beaches north, south and south-west of the rutile dump, at sites A, H, K, R and W of Fig. 25, five days later (i.e., 37 days after dumping) failed to reveal any trace of the rutile.

At this time (August 3rd) it was reported by Portland Harbour Trust officers that the thickness of the sand at the sea wall was 3 ft. greater than was normal for this time of the year. This accords with the slight seaward movement of the rutile, and accounts for its maintained concentration in and around the original dumping site.

Pyrite at the Breakwater Site

Pyrite was used as a marker mineral on the harbour floor as well as on the beach in Discovery Bay, on the assumption that if the two tests were made more or less simultaneously there would be no interference from one test to the other during the period of the testing campaign. As indicated above, no interference occurred, although the Discovery Bay pyrite moved eastwards more rapidly than was expected.

The pyrite was dumped at the point of intersection of the Main Breakwater reference line and a centre line on Julia Street, Portland (Fig. 25). Test samples were taken at first daily and later at three- to four-day intervals, at sampling stations spaced 250 ft. apart along the NW, NE, SW and SE compass bearings from the pyrite dump. The depth of water at the site was 40 ft.

Movement of the pyrite across the harbour floor, together with the time in days taken to travel the various distances in the several directions, are shown in Fig. 25.

The pyrite moved 250 ft. SW and 250 ft. SE in one day after dumping, but took eleven days to move a similar distance NW and NE. Thereafter it spread at a fairly uniform rate, but favouring the southerly directions. After 31 days it had reached stations 2000 SW, 2000 SE, 1500 NW and 1500 NE, equivalent to an average rate of movement of 65 ft. per day to the SW and SE, and of 45 ft. per day to the NW and NE.

Movement onshore in the westerly direction was much faster. After 24 days, pyrite appeared at the rutile dump stations, having travelled 4200 ft. westwards in 24 days, while the rutile had travelled only 750 ft. eastwards in 26 days. The average onshore (westward) rate of movement of the pyrite was thus 175 ft. per day, in contrast to an offshore movement of the rutile of 30 ft. per day.

As a check, 30 to 31 days after the pyrite was dumped on the harbour floor the harbour beaches were sampled at five stations (A, H, K, R and W) shown in Fig. 25, and pyrite was found at all five in the proportions shown in Table 8.

TABLE 8

Approximate Proportions of Pyrite on First Appearance at various Sampling Stations in Portland Harbour, and Time (in days) taken to reach Sampling Stations

Distance from Dump	Parts by weight per 100,000,000											
	NW	NE	SW	SE	A	H	K	R	W	R.D.	N	E
250′	pr. (11)	pr. (11)	12 (1)	12 (1)	—	—	—	—	—	—	—	—
500′	42 (11)	21 (17)	pr. (11)	pr. (11)	—	—	—	—	—	—	—	—
750′	350 (24)	650 (24)	6 (17)	45 (17)	—	—	—	—	—	—	—	—
1000′	—	—	—	18 (17)	—	—	—	—	—	—	—	—
1500′	550 (31)	120 (31)	42 (24)	1350 (27)	—	—	—	—	—	—	—	—
2000′	—	—	90 (30)	350 (31)	—	—	—	—	—	—	—	—
2600′	—	—	—	—	—	—	—	6 (31)	—	—	—	—
2700′	—	—	—	—	—	—	—	—	3 (31)	—	—	—
3050′	—	—	—	—	18 (30)	—	—	—	—	—	—	—
3750′	—	—	—	—	—	—	27 (30)	—	—	—	—	—
4000′	—	0 (43)	—	90 (43)	—	—	—	—	—	—	24 (43)	0 (43)
4200′	—	—	—	—	—	—	—	—	—	12 (24)	—	—
5100′	—	—	—	—	—	54 (31)	—	—	—	—	—	—

(Figures in parentheses indicate number of days to first appearance of pyrite at sampling stations)

KEY:

NW, NE, SW, SE, N and E are compass bearings along which directions test samples were taken.

A = original sampling station 103, Lady Bay.
H = original sampling station 128, beach at end of Fern Street, Portland.
K = middle of Henty Beach.
R = head of bay west of Battery Point and south-east of Portland Harbour Trust offices.
W = original sampling station 130, near Portland Harbour Trust offices.
R.D. = site of rutile dump, original sampling station 126, between Railway Pier and Deep-water Pier.
pr. = present (approximate proportions of pyrite not determined).

Movement directly onshore to the north-west was the strongest, the greatest concentration (54 parts in 100,000,000) being found at station H, which is most distant (5100 ft.) of the five beach stations from the dumping site. Movement in this direction had been in excess of 165 ft. per day, since the exact day of arrival of pyrite at station H was not known. The distance to the other stations and the concentrations attained at each are shown in Table 8.

This marked increase in the rate of movement onshore is attributed to the pyrite entering progressively shallower water shorewards, where it became subject to transport by waves of translation.

To test the offshore movement of the pyrite east of the dump, a series of samples was taken 43 days after dumping at stations situated 4000 ft. N, 4000 ft. NE, 4000 ft. E and 4000 ft. SE of the dump. As shown in Table 8, pyrite was found at 4000 ft. N in concentrations of 24 parts per 100,000,000 and at 4000 ft. SE in concentrations of 90 parts per 100,000,000, but no pyrite was detected either at 4000 ft. NE or at 4000 ft. E.

At most stations where successive samples were taken at short intervals of time following the first appearance of the pyrite, the amount of pyrite present increased in the later samples, more particularly along the SE line of sampling stations (see Table 8).

Further sampling at the four 1500-ft. stations at an interval of between 62 to 68 days after the pyrite first appeared there showed that the amount of pyrite present in the sand had begun to decline at all four stations. As shown in Table 9, the

TABLE 9

Percentage Decline in Pyrite Content at the 1,500 NW, NE, SW and SE Sampling Stations, 62 to 68 days after Dumping of the Pyrite

Sampling Station	Number of days between samplings	Number of pyrite grains		Percent decline in pyrite content
		First sampling	Second sampling	
1,500′ NW	62	184	140	24
1,500′ NE	62	43	33	23
1,500′ SW	68	12	11	8
1,500′ SE	65	454	450	1

(The figures listed under the column "Number of pyrite grains" were obtained from grain counts of the Superpanner "head" concentrates derived from the treatment of 50 gram samples of the —52 fractions of the sands from each sampling station.)

decline was much more pronounced at 1500 ft. NW and 1500 NE than at 1500 ft. SW and 1500 ft. SE. At 1500 SE, which showed much the greatest concentration of pyrite, the decline was least and of no great significance.

Conclusions

The sands of the Portland coast consist essentially of organogenic material with admixed detrital minerals derived from various sources—

(1) Shell fragments, etc., derived from the fauna of the sea floor.
(2) Basaltic minerals shed from the basalts and tuffs exposed in the cliffs of Bridgewater Promontory and Portland Harbour. These mineral grains are markedly angular and chemically relatively unstable.

(3) Minerals derived from granitic, metamorphic and sedimentary rocks (i.e., = the granitic-metamorphic group herein) brought from distant sources. These minerals are chemically stable varieties and occur as well-rounded grains.

The shell fragments, etc., comprise about 90% of the sand in the Portland Harbour area, as compared with only 75% of the sands of Discovery Bay and Bridgewater Promontory.

The harbour sands are distinctly grey, from the presence of a high proportion of dark shell fragments, whereas the sands of the exposed beaches are relatively free from dark shell fragments. This is regarded as evidence that a considerable proportion of the sand is derived from the shells of animals living on the harbour floor and the adjacent rocks (also *cf.* Sprigg, 1952, p. 101).

The heavy minerals in the harbour sands are predominantly basaltic, indicating that they are also derived from the vicinity. The proportion of granitic-metamorphic heavy minerals and quartz is low compared with the sands on the more exposed beaches, indicating that only a relatively small proportion of the sand could have been derived by drift from distant sources. A little of the quartz in the harbour sands could have been contributed by the rivers entering Portland Bay.

Study of the distribution of the basaltic minerals reveals that they have drifted in small quantities for about 26 miles north-westwards along Discovery Bay beach from their point of origin at Cape Bridgewater, and that basaltic minerals have drifted eastwards from the Bridgewater Promontory to beyond the Eumeralla River mouth in rather greater volume. The conclusion is that stronger drift prevails to the north-east from the Bridgewater Promontory than to the north-west.

The sands in Portland Harbour are distinctly finer-grained than those on the exposed ocean beaches, and this, combined with their distinctly lower detrital mineral grain content, indicates that such sand drift prevailing towards the north-east largely by-passes the harbour area, the sand fetching up on the eastern beaches of Portland Bay.

The evidence of the detailed examination of the natural sands and contained artificial contaminants along the Portland coast thus indicates that only a minor amount of sand is entering Portland Harbour by coastwise drift, and that the observed movements of sand on to and away from the harbour beaches are mostly local movements.

These deductions arise from the study of the nature and distribution of the sands as determined by the operation of marine agencies over a considerable period of recent geological time, and the results of the short-term experiments on the movements of the marker minerals are generally in accord with these deductions.

One of the most striking points that emerges from the marker mineral experiments relates to the very different rates of their migration in the several environments tested. These rates are summarized in Table 10. The rate of movement eastwards and north-eastwards from Cape Bridgewater and Lawrence Rocks is of a very different order of magnitude from the other movements. Presumably this is because the one is a relatively unhindered movement parallel to the set of the waves and currents occurring in relatively deep water, where wave base stirs the sand on the ocean floor sufficiently at the passage of each wave to permit either—

(a) a current setting in the same direction to move the sand particles forward at each stirring process; or

TABLE 10

Approximate Rates of Movement of the Marker Minerals from the Original Dumping Sites

Region	Rate of Movement (yards per day)
Portland Bay	
(i) Narrawong Beach	4–6
(ii) Sea Wall	10
(iii) Harbour Floor	
(*a*) outer	15–20
(*b*) inner	55–60
Discovery Bay	
Northwest	70
Cape Bridgewater	
East	1175–3500
Lawrence Rocks	
East	440+**

** Minimum rate only.

(b) the circular movement of the particles initiated by the passage of each wave being interrupted by the sea floor, so that with the passage of each wave the particles are picked up, moved forward some distance by the forward-moving half of the orbital motion, and set down again, so that movement occurs by a process of saltation.

The movements north-westwards along Discovery Bay, and east and west along Narrawong Beach, occur by longshore drift, which is a hindered movement oblique to the set of the waves. The swash moves the sand obliquely up the beach, while the backwash returns it normal to the beach slope, resulting in a zig-zag progression both easterly and westerly, but rather more prominently easterly at both localities. The much slower rate of movement on Narrawong Beach is attributed to the smaller size of the waves resulting from its rather more sheltered position.

The slow movement on the harbour floor is also attributed to the relatively small size of the waves reaching this part of Portland Bay, but the speed of movement is sharply accelerated when the sand enters the zone of waves of translation.

A second significant point is the observation that the greater proportion of any sand moving eastwards along the Bridgewater Promontory coast by-passes Portland Harbour and crosses the mouth of Portland Bay in a north-easterly direction, fetching up on its eastern coast between the Fitzroy River and Cape Reamur. This means that most of the sand in the harbour area is mainly of local origin.

The same by-passing tendency operates across the western end of Bridgewater Bay.

A third striking result is that the movement of the brown garnet on Narrawong Beach proved that there was no strong drift of sand westerly around the head of Portland Bay, at least during the period of testing. In fact such movement as was detected was more strongly to the east. Given a period of strong south-easterly winds, however, some westerly movement might develop.

The observations on marker mineral movements and the conclusions reached concerning sand movements over long periods of time from the study of the composition of the various sands are also supported by the following field observations:

(i) From west to east on the eastern side of Portland Bay there is a progressive increase in the amount of easterly to south-easterly deflection of the mouths of the three main rivers flowing into the bay. Thus, nearest to the harbour area, the mouth of the Surrey River has been deflected two miles east-north-easterly; further east, the mouth of the Fitzroy River has been deflected four miles easterly; still further east, the mouth of the Eumeralla River has been deflected eight miles in a south-easterly direction. These deflections are attributed to the effects of a long-term easterly drift of sand along the coast.

(ii) Coupled with (i) is a progressive development of sand dunes from the Surrey River towards Cape Reamur. This points to an increasing supply of sand to the coast in an easterly to south-easterly direction on the eastern side of Portland Bay.

Of considerable importance is the observation that the predominant movement of sand on the harbour floor during the period of testing has been onshore (north-westwards, westwards and south-westwards), with some tendency to move south-eastwards. The strong onshore movement of the pyrite, combined with the weak offshore movement of the rutile, and the fact that beach height at the sea wall was maintained throughout the testing period, proves that a seasonal period of dominant local onshore drift prevailed in the harbour.

Sooner or later, seasonal changes will reverse this trend to a dominantly offshore drift, which will remove sand from the harbour beaches and spread it out over the harbour floor. The agents and processes causing this are strong onshore winds which build up the sea water against the land. Ultimately this cannot be supported, and so narrow, well-defined currents or rips move seawards with strong velocities, taking with them large quantities of sand offshore to deeper water, where they are then made available for longshore transport (Shepard, Emery and La Fond, 1941). Such sand as moves out to the mouth of Portland Bay (*cf.* south-easterly movement of pyrite from the harbour dump) would be caught up in the north-easterly trend across the bay mouth, and be removed from the area. The sands on the harbour floor are constantly being added to by comminution of shelly, etc., material derived from organisms indigenous to the area, and to a lesser degree by detrital material derived locally from the cliffs, and one of the principal effects expected here is one of seasonal oscillation of sand between the harbour beaches and the harbour floor.

The building of the breakwaters may slow up but not necessarily stop onshore movement of sand. The breakwaters will, however, reduce the force of agencies that tend to move the sand offshore (*cf.* rip currents above), in which event slow siltation of the harbour should occur, unless it is cleared by dredging.

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